PERFORMANCE ANALYSIS OF IMC BASED CASCADE CONTROL SYSTEM AND COMPARATIVE STUDY OF 1DF & 2DF IMC CONTROLLER

Thesis submitted in partial fulfillment of the requirements for the degree of

Master of Technology

In

Electronics &Instrumentation Engineering

By

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NATIONAL INSTITUTE OF TECHNOLOGY

ROURKELA

CERTIFICATE

This is to certify that the thesis report titled **“PERFORMANCE ANALYSIS OF IMC BASED CASCADE CONTROL SYSTEM AND COMPARATIVE STUDY OF 1DF AND 2DF IMC CONTROLLER”** Submitted by **Miss. ANITA LAKRA (**Roll No: 212EC3155) in partial fulfillment of the requirements for the award of Master of Technology in the Electronics and Communication Engineering with specialization in **“Electronics and Instrumentation Engineering”** during Session 2012-2014 at National Institute of Technology, Rourkela and is an authentic work carried out by him under my supervision and guidance.

From the best of my knowledge, the matter embodied the thesis has not been submitted to any other University or Institute for the award of any Degree or Diploma.

……………………………...

Prof. Tarun Kumar Dan

Place: Dept. of Electronics and Comm. Engineering

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Anita Lakra

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CONTENTS

ABSTRACT

In this project, performance analysis of IMC (Internal Model Control) based Cascade Control and comparative study of 1DF (One-Degree of Freedom) and 2DF (Two-Degree of Freedom) IMC controller has been discussed. Based on considerations about the expected operational modes of the inner loop as well as outer loop controller are selected from the 1DF and 2DF IMC control system. A design method for both 1DF and 2DF IMC systems have been designed with ideal models which provide the greatest probable performance compatible with noisy measurement for intrinsically stable processes.

An important thing is that for designing of IMC controllers is the capability to show the time response of the loop transmission. The MATLAB and SIMULINK software has been used for designing of the 1FD and 2DF controllers, where the controllers and processes has been performed in the blocks. The 1DF control systems present the IMC design methods for intrinsically stable linear processes where the disturbance arrives directly into the process output.

The 2DF control systems are used for stable processes or for inherently unstable processes where the disturbances proceeds over a lag or over a lag the process whose process time constants are in the order of lag time constants of the process or greater than the process lag time constant .

In IMC cascade systems, to obtain the best set-point tracking and disturbance rejection the cascade control inner loop must be designed and tuned such as a 2DF controller.

LIST OF FIGURES

LIST OF ACRONYMS

1DF	One-Degree of Freedom
2DF	Two-Degree of Freedom
IMC	Internal Model Control
PID	Proportional Integral Derivative

CHAPTER-1

INTRODUCTION

1.1 Literature Survey

Coleman Brosilow, Babu Joseph have proposed a methods of model based control for IMC cascade control system [1]. They designed 1DF and 2DF controller to increase the performance of the IMC cascade control system. They defined the 1DF, 2DF and IMC cascade structure.

Jaun Chen, Lu Wang and Bin Du have proposed a improved structure of internal model control (IMC) for the process which is not stable having delay time [4]. They designed new a structure using a combination of feedback, feed forward, cascade and IMC control strategy.

Ming T. Tham have proposed the designing procedure of internal modal control method [6]. He defined the IMC strategy, basic principal, IMC based PID controller design approach.

B. Wayne Bequette have proposed the Process control modeling, design and simulation for the cascade control system [11]. He defined the tuning of primary and secondary controller to cascade control system.

1.2 Objective

The objective of this thesis is to design an IMC cascade structure and Compare the output response of the single-loop and IMC cascade control system to a step set-point change and step disturbance. To design the 1DF and 2DF IMC controller and compare the output response to a set point changed.

To minimize the influence of disturbance on the primary process of the cascade control system through the operation of a secondary or inner control loop about a secondary process for desired calculation.

1.3Thesis Outline

This thesis involves 5 chapters. After the introduction, the remaining portion of the thesis is organized as follows:

Chapter 2 1DF IMC Controller

In this chapter the 1DF, IMC construction and properties has been discussed. The design method of 1DF Internal Model Control systems having process models which give the most effective probable response compatible with noisy measurement for intrinsically stable processes.

Chapter 3 2DF IMC Controller

This chapter introduces the 2DF Internal Model Control systems and explains its benefits above one-degree of freedom IMC if step disturbances arrive through process lag. The design method of 2DF Internal Model Control systems with process models which provide the effective probable response, reliable with noisy measurement for intrinsically stable process and intrinsically stable processes.

Chapter 3 IMC Based Cascade Control System

In this chapter the basic configuration of the cascade control system and IMC based cascade control system has been discussed. To present an alternative approach about a cascade control system that lead to improved performance.

Chapter 5 Conclusion

The conclusion remark for are the chapters are presented in this chapter.

CHAPTER-2

1DF IMC SYSTEM

2.1 INTRODUCTION

In this chapter the designing method of the feedback controller has been discussed, where we insist the output of an instinctively stable process to perform in a preferred way to a set-point variation and reduce the special impact of disturbances that arrive directly into the output of the process [1]. Suppose, we have a calculated model of the process, to acquire a quantitative controller design, which permit us to predict the response of the process output to the disturbances and to control effort. First of all we consider that, the calculation done from the model is an excellent exemplification of the process, second the process is linear and third there are limited restrictions on the control effort and so it will accept on any number from plus to minus infinity[6].

The IMC structure is shown in the below Fig. (2.1). The IMC theoretically give a permission, to focus on the design of controller without being worried about the stability of the control system if the process model is the best explanation for a stable process P(s)[5][4].

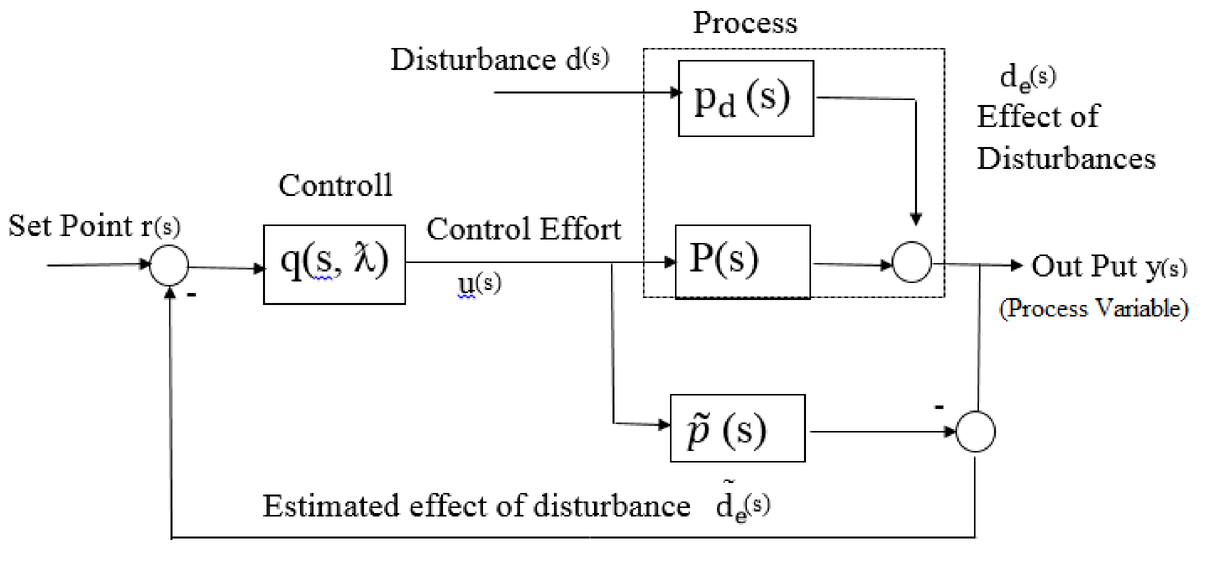

Figure 2.1 The IMC System.

The various parameters used in the IMC system shown above are as follows:-

r(s) = Set-Point

q(s, ƛ) = IMC controller

p(s) = Process

$\tilde{p}$ (s)= Process Model

d(s) = Disturbance

$\tilde{d}_e$(s) = Estimated Disturbance

u(s) = Manipulated Input (Controller Output)

y(s) = Process Variable

ƛ= Filter Time Constant

2.2 PROPERTIES OF INTERNAL MODEL CONTROL

2.2.1 Transfer functions

The representation of input as well as the output of a single loop feedback system is called the transfer function, which have the transmission in the forward direction from the input to the output. The transfer function among the input d(s) and set-point r(s) and also the process output y(s) is given in Fig. (2.1). The alternate IMC configuration system is shown in the Fig. (2.2).

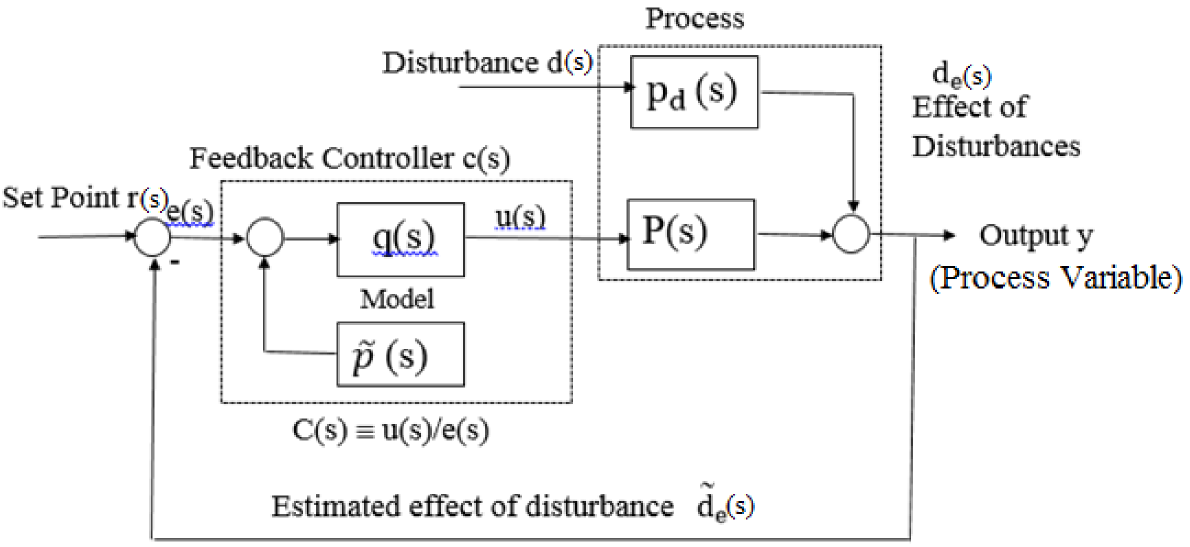

Figure 2.2 Alternate IMC Configuration Systems.

The feedback controller c(s) from the Fig. (2.2) gives

$$c(s) = \frac{u(s)}{e(s)} = \frac{q(s)}{(1-q(s)\tilde{p}(s))} \tag{2.1}$$

The minus sign in the denominator given by Eq. (2.1) came through the positive feedback about q(s).

The input output relationship for Fig. (2.2) are given by

$$\frac{y(s)}{r(s)} = \frac{p(s)(qs)}{(1+p(s)c(s))} \tag{2.2}$$

$$\frac{y(s)}{d(s)} = \frac{p_d(s)}{(1+p(s)c(s))} \tag{2.3}$$

$$\frac{u(s)}{r(s)} = \frac{c(s)}{(1+p(s)c(s))} = \left(\frac{y(s)}{r(s)}\right) p^{-1}(s) \tag{2.4}$$

$$\frac{u(s)}{d(s)} = \frac{-p_d(s)c(s)}{\left(1+p(s)c(s)\right)} = -\left(\frac{y(s)}{d(s)}\right) c(s) \tag{2.5}$$

By substituting Eq. (2.1) into Eq. (2.2) and Eq. (2.3) we get result

$$y(s) = \frac{p(s)q(s)r(s)}{(1+\left(p(s)-\tilde{p}(s)\right)q(s))} \tag{2.6}$$

$$y(s) = \frac{(1-\tilde{p}(s)q(s))p_d(s)d(s)}{(1+\left(p(s)-\tilde{p}(s)\right)q(s))} \tag{2.7}$$

2.2.2 Non Offset Property of IMC

When the Laplace variables are replaced by zero, then the steady state gain of some stable transfer function is achieved. If given Eq. (2.6) and (2.7) are stable and the controller q(0) steady state gain is chosen to be the inversion of the model gain, then the denominator gain. Then the denominator gain of the Eq. (2.6) and (2.7) will be p(0)q(0).

For the ideal control system

$$y(s)= r(s) \tag{2.8}$$

$$\frac{y(s)}{d(s)} = 0 \tag{2.9}$$

From equation (2.8) and (2.9) we consider

$$p(s)\, q(s) = 1, \quad \tilde{p}(s) = p(s) \tag{2.10}$$

So that's why we want a perfect model for perfect control, and from Eq. (2.10), the model should be invert perfectly by the controller.

2.2.3 Design of IMC for No Disturbance LAG

In this section, we discuss about the disturbance lag p_d (s) which have a unity.

The 1st order lag along with dead time process is given by

$$p(s) = \frac{ke^{-\theta s}}{\tau_1 s+1} \;;\; p_d(s) = 1 \tag{2.11}$$

The inverse of the process p(s) from Eq. (2.11) is

$$p^{-1}(s) = \frac{\tau_1 s+1}{k} e^{\theta s} \tag{2.12}$$

From Eq. (2.12) we realized that, the controller is the converse of the process gain **k**. So controller q(s) is given by Eq. (2.11) as

$$q(s) = \frac{\tau_1 s+1}{k(\lambda s+1)} \tag{2.13}$$

Where λ = a filter time constant or tuning parameter. A filter parameter will choose to avoid unnecessary noise amplification and to provide accommodations modeling error [3].

In the case of minor modeling error, the time constant of a filter λ can be smaller as compared to the actual time constant of the process τ_1 and the controller Eq. (2.13) will be a lead network.

The transfer function for the perfect model loop response is represented by

$$y(s) = \frac{e^{-\theta s}}{(\lambda s+1)} r(s) + \left(1 - \frac{e^{-\theta s}}{(\lambda s+1)}\right) d(s) \tag{2.14}$$

For avoiding the extreme noise amplification, the λ will be taken, therefor the controllers large frequency gain q(s) is not greater than 20 times of its small frequency gain. This criterion can be expressed as

$$\left|\frac{q(\infty)}{q(0)}\right| \leq 20 \tag{2.15}$$

The generalized control design scheme, for the 1st order dead and lag time process is

$$p(s) = \frac{N(s)}{D(s)} e^{-\theta s} \tag{2.16}$$

Where,

N(S) and *D(S)* are s domain polynomials.

2.2.4 IMC Design for Processes having No Zeroes near the Imaginary Axis or in the Right Half of the s-Plane

If the process numerator *N(s)* has been no zeroes in the right side of the s-plane or adjacent the imaginary axis, the converse of the process model is overly oscillatory and stable. The IMC controller can be chosen as

$$q(s) = \frac{D(s)}{N(s)(\lambda s+1)^r} \tag{2.17}$$

Where,

r = the relative order of (*N (S)* / *D (S)*).

From Eq. (2.15), the filter parameter λ in Eq. (2.17) should satisfy

$$\lambda \geq \left(\lim_{n\to\infty} \frac{D(s)N(0)}{20s^r N(s)D(s)} \right)^{1/r} \tag{2.18}$$

2.2.5 Design of Process for IMC having Right Half Plane Zeroes

When the numerator N(s) in Eq. (2.16) has factored of the form ($\boldsymbol{\tau}$s+1) or ($\tau^2 s^2$-2$\boldsymbol{\tau}$ȿs+1), where $\boldsymbol{\tau}$ and ȿ larger than zero and its converse is not stable. So this situation the Internal Model Control controller cannot be made as given by Eq. (2.17). For that we consider that the model shown by Eq. (2.16) may be written as

$$p(s) = \frac{N_-(s)N_+(s)}{D(s)} e^{-\theta s} \tag{2.19}$$

Where,

$N_-(s)$ Involves only zeroes of the left side of s-plane, no one of which has lesser damping ratios.

$N_+(s)$ Involves only zeros of the right-half plane that can be written as

$$N_+(s) = \prod_{i\,j} (-\tau_i\, s+1)\ (\tau^2{}_j s^2 - 2\tau_j\, \xi_j + 1) \tag{2.20}$$

τ_i , $\tau_j > 0$; $0 < \xi < 1$

Here, the gain of $N_+(s)$ is one.

The *Integral Square Error* optimal IMC controller for Eq. (2.19) is

$$q(s) = \frac{D(S)}{N_-(s)N_+(s)(\lambda s+1)^r} \tag{2.21}$$

The resulting loop response is given by,

$$y(s) = p(s)q(s) = \prod_{i,j} \left(\frac{-\tau_i s+1}{\tau_i s+1}\right) \left(\frac{\tau_j{}^2 s^2 - \tau_j \xi_j s+1}{\tau_j{}^2 s^2 + \tau_j \xi_j s+1}\right) \frac{e^{-\theta s}}{(\lambda s+1)^r} \tag{2.22}$$

τ_i, $\tau_j > 0$; $0 < \xi_j < 1$.

The resulting loop response in Eq. (2.22) is optimal is an *Integral Square Error* sense for a filter parameter λ of zero, and that is suboptimal for finite λ. If λ is zero, then the loop transfer function given by Eq. (2.22) is known as all pass, then the magnitude of the frequency response is one above all frequencies.

2.3 SIMULATION RESULTS AND DISCUSSIONS

2.3.1 The FOPDT Process in IMC Controller

The process model is,

$$p(s) = \frac{ke^{-\theta s}}{\lambda s+1}; p_d(s) = 1$$

$$q(s) = \frac{(\lambda s+1)}{k(\lambda s+1)}$$

Where,

λ= Filter time constant

The transfer function of the perfect model loop response by p(s)q(s) with p(s) = p̃(s). By using the given equations for p(s) and q(s) gives

$$y(s) = \frac{e^{-\theta s}}{(\lambda s+1)}\, r(s) + \left(1 - \frac{e^{-\theta s}}{(\lambda s+1)}\right) d(s) \tag{2.23}$$

Where,

ϴ= 1 and λ=0.05 and 1.0.

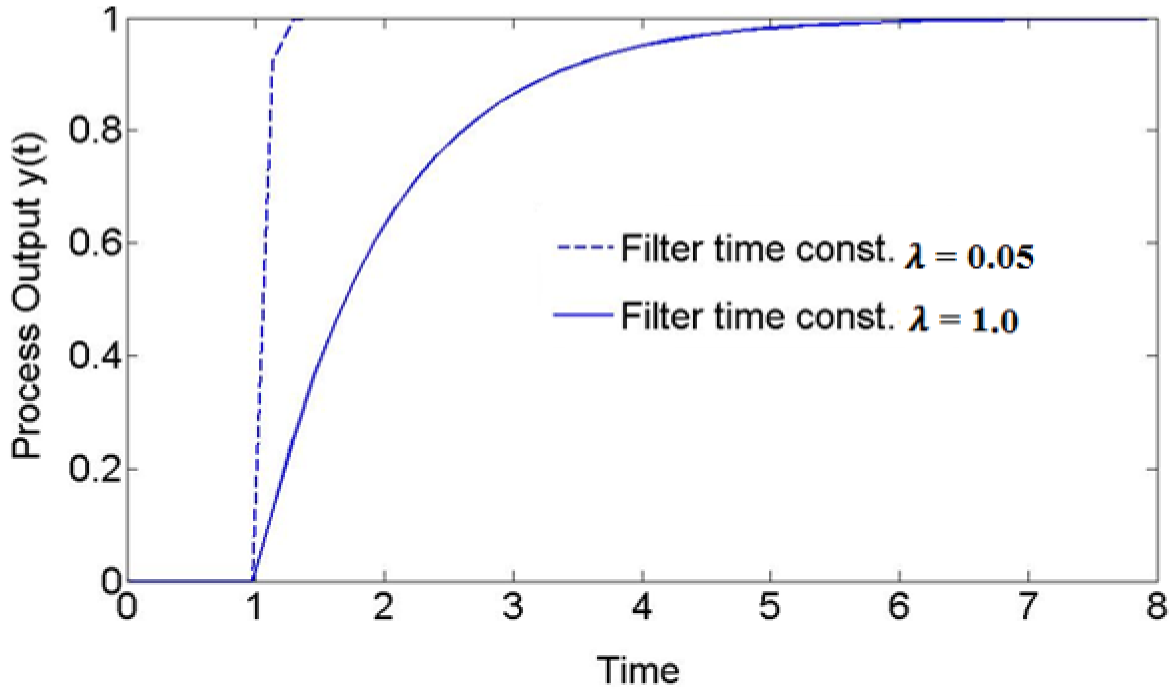

Figure 2.3 Perfect model IMC step response for FOPDT.

The choice of the filter parameter λ, for the given equation y(s) depend on the acceptable noise amplification through the controller in addition to modeling error. By increasing the value of λ the settling time is also increasing and affect the stability.

2.3.2 A Process Model having Low Damping Ratio Zeroes

The process model is represented by

$$p(s) = \frac{s^2 + 0.001s+1}{(s+1)^4} \tag{2.24}$$

The controller is

$$q(s) = \frac{(s+1)^4}{(s^2 + 0.001s+1)(\lambda s+1)^2}$$

After modifying a better, IMC controller is

$$q(s) = \frac{(s+1)^4}{(s^2+2\varsigma\, s+1)(0.22s+1)^2} \tag{2.25}$$

Where,

ς = Damping Ratio, λ = 0.22(filter time constant)

The resulting transfer function of the loop response p(s)q(s) is

$$p(s)\, q(s) = \frac{s^2 + 0.001s+1}{(s^2+2\varsigma s+1)(0.22s+1)^2} \tag{2.26}$$

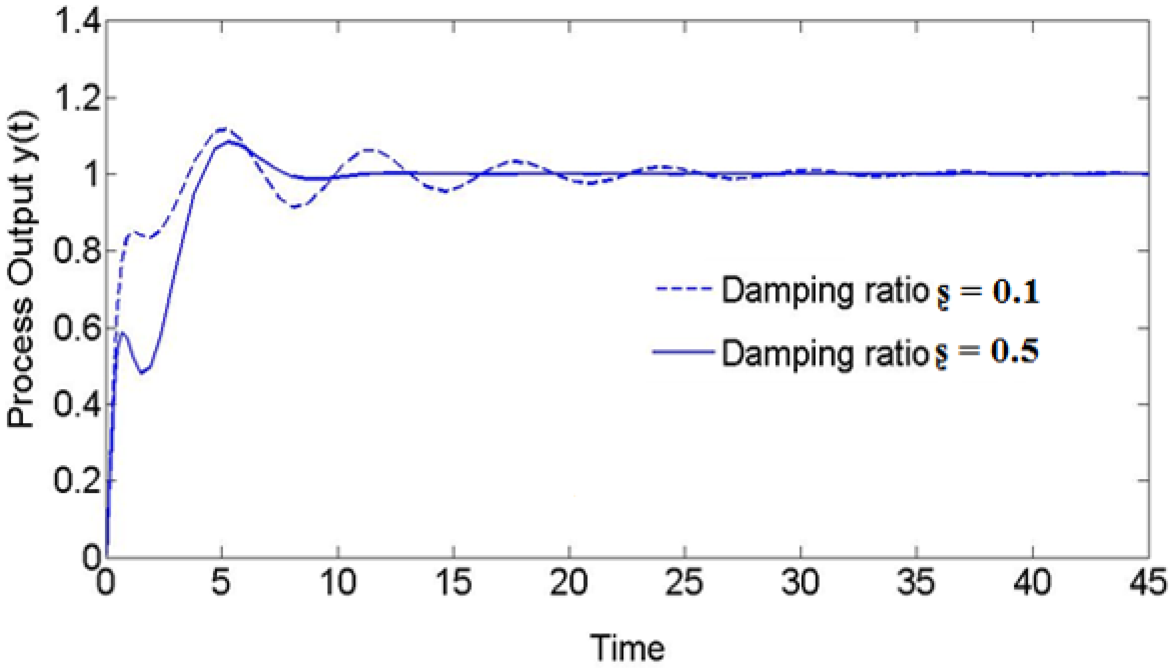

Figure 2.4 Perfect Model Loop Response for p (s) q (s) = $\frac{(s^2+0.001s+1)}{((s^2+2ȿs+1)\,(0.22s+1)^2)}$.

Figure 2.4 shows the perfect model loop response given by Eq. (2.26) for the damping ratio of 0.1 and 0.5. For the damping ratio 0.5 controllers give a lesser amount of oscillatory response than that, gives by a controller damping ratio of 0.1. In another way, the controller response for ȿ = 0.5 is more sluggish than, for the ȿ = 0.1.In another case we use a process information to select the most suitable controller.

2.3.3 A Process having One Right-Half Plane Zeroes

The process model is,

$$p(s) = \frac{(s-1)}{27(s+\frac{1}{3})^3} \quad = \frac{-1(-s+1)}{(3s+1)^3} \tag{2.27}$$

The IMC controller is

$$q(s) = \frac{-1(3s+1)^3}{(s+1)(\lambda s+1)^2}$$

(2.28)

The perfect model loop response is

$$p(s)\ q(s) = \frac{(-s+1)}{(s+1)(\lambda s+1)^2} \quad (2.27)$$

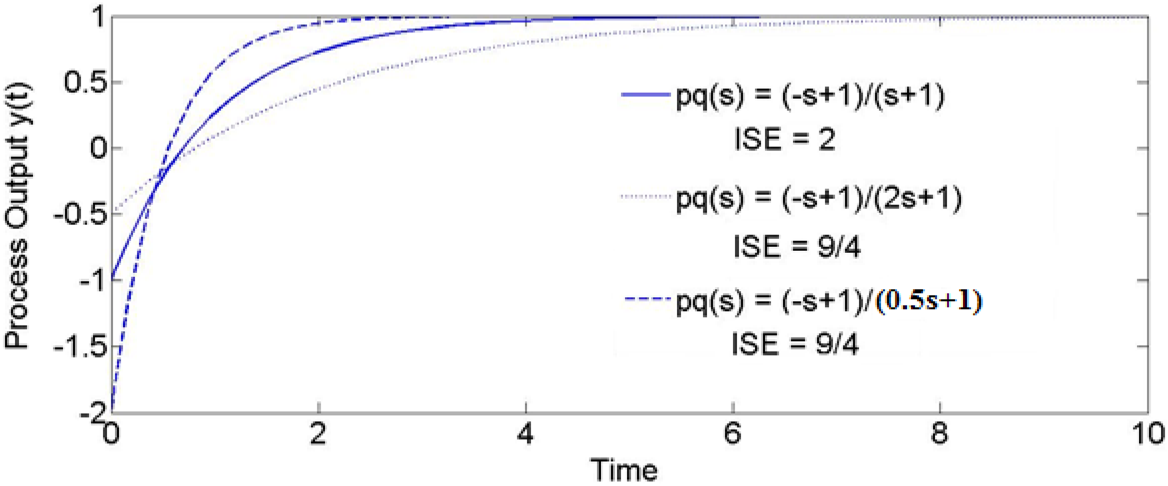

Figure 2.5 A Process Loop Response with One Right Half of Plane Zeros.

The performance of the system increases with decreasing the value of filter time constant λ. Fig. 2.5 compare the ISE open loop transmission to step responses by increasing as well as decreasing the filter parameter.

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CHAPTER-3

2DF IMC SYSTEM

3.1 INTRODUCTION

In this chapter, we discussed about the 2DF IMC control systems, which is basically used for both stable and un stable processes, whose time constants are in the order of, the lag time constants or greater than the process lag time constant . Here we also discussed about the comparative behavior of a 1DF and 2DF control system. In general, there are no advantages of a 2DF controller as compared to 1DF controller while the lag time constant of the disturbance is relatively smaller than the process lag time constant, or when the pass over of disturbance in a stable process having smaller lag time constants such that it leads time constant. The MATLAB and SIMULINK software has used for designing of the 2DF controllers, where the controllers and processes has performed in a blocks.

The configuration of the 2DF IMC controller is shown in the Fig. 3.1 [1].

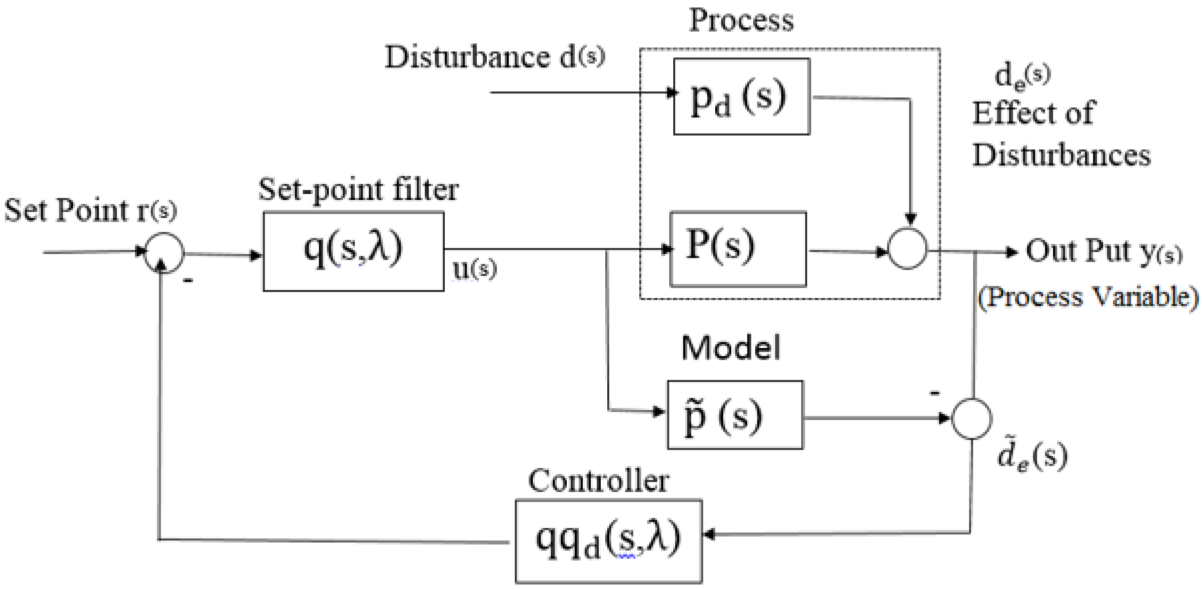

Figure 3.1 2DF IMC Structure.

The controller $qq_r(s,\lambda)$ in Fig. (3.1) is designed to reject disturbances while the set-point refers to the set-point controller as the set-point filter in order to be dependable with an industrial terminology.

From Fig. (3.1) we can write the perfect model output and a control effort response is

$$y(s) = \tilde{p}(s)\, q(s,\lambda)\, r(s) + (1-\tilde{p}(s)qq_d(s,\lambda))p_d\,(s)d(s) \tag{3.1}$$

$$m(s) = q(s, \lambda)r(s) + qq_d(s, \lambda)p_d(s)d(s) \tag{3.2}$$

3.2 DESIGNS FOR STABLE PROCESS

3.2.1 Design of the Set-Point Filter q(s, λ)

The set-point filter q(s, λ) in Fig. 3.1 is considered as a 1DF controller, using the method which is given in the chapter 1. However, there is usually certainly not a noise on the set point and there is no noise amplification bound in λ.But, very lesser values of y are not selected due to the probability of control effort saturation.

3.2.2 Feedback Controller design, qq_d (s, λ)

The perfect model TF among output as well as disturbance for Fig 3.1 is

$$y(s) = (1-\tilde{p}(s)qq_d(s))\tilde{p}_d(s)d(s) \tag{3.3}$$

To design qq_d(s, λ) for an ideal model, it is helpful to take qq_d(s, λ) to be made of two stage q(s, λ) as well as qq_d(s, λ). The processes for the design are as follows:

(i) Choose q(s, λ) as it specified in the chapter 1. This is, q(s, λ) inverts a part of the process model $\tilde{p}$(s). The filter of the controller is chosen as $1/(\lambda s + 1)^r$, where r is the relative order of the portion of the process model which is inverted by q(s, λ).

(ii) Choose q(s, λ) as

$$q_d(s,\lambda,\beta) = \frac{\sum_{i=0}^{n} \beta_i s^i}{(\lambda s+1)^n} \;;\; \beta_0 \equiv 1, \tag{3.4}$$

Where n is the no. of poles in$\tilde{p}$(s) can be cancelled by the zeros of (1-$\tilde{p}$(s)qq_d(s)).

(iii) Choose a sample value for the filter parameter λ.

(iv) Find the value of $\beta_i$by solving Eq. (3.5) for each of the n different poles of$\tilde{p}_d$ (s) that are to be detached from the response of disturbance.

$$(1-\tilde{p}(s)qq_d(s,\lambda,\beta))\Big|_{s=1/\tau_i} = 0; \qquad i = 1,2,\ldots.n, \tag{3.5}$$

Whereτ_i is the time constant conjoint with the i^{th} pole of $\tilde{p}_d(s)$.

If $\tilde{p}_d(s)$ have repeated poles, then the derivatives of the Eq. (3.5) are taken to be zero, up to order one less than the number of repeated poles. For example, if $\tilde{p}_d(s) = 1/(\tau_j s + 1)^r$then we determine,

$$(1- \tilde{p}_d(s)\, qq_d(s,\lambda,\beta))\Big|_{s=-1/\tau_j} = 0 \tag{3.6}$$

$$\frac{d^k}{ds^k}(\tilde{p}(s)qq_d(s,\lambda,\beta))\Big|_{s=-1/\tau_j} = 0; \qquad k = 1,\ 2,\ldots\ldots r\text{-}1 \tag{3.7}$$

(v) Change the value for λ and repeat step (iv) until the preferred noise amplification is received. A few tests are generally enough to receive a noise amplification factor close sufficient to the required value. Definitely, one is capable of solving simultaneously for that, $\beta_i$that fulfill the step (iv) and the preferred noise amplification. However, resolving simultaneously for β_i and λ go for the solution of a set of nonlinear equations [2].

3.3 DESIGNS FOR UNSTABLE PROCESSES

3.3.1 Internal Stability

If the process is not stable, then 1DF as well as 2DF IMC systems are, internally not stable. That is, applying only limited inputs will reason more than one signals in the block diagram Fig. (2.1) and (3.1) to precede without bound no word how the controller q(s) as well as qq_d (s) are selected [9].

By description, a control system in intrinsically stable for limited inputs, intermeddle at any instant of the control system; originate limited responses at any other instant. A linear time invariant system is internally stable if the transfer function during any two instant of the block structure is stable. In the Fig. (2.2), we hope for the summation of the two input u_1 and u_2.

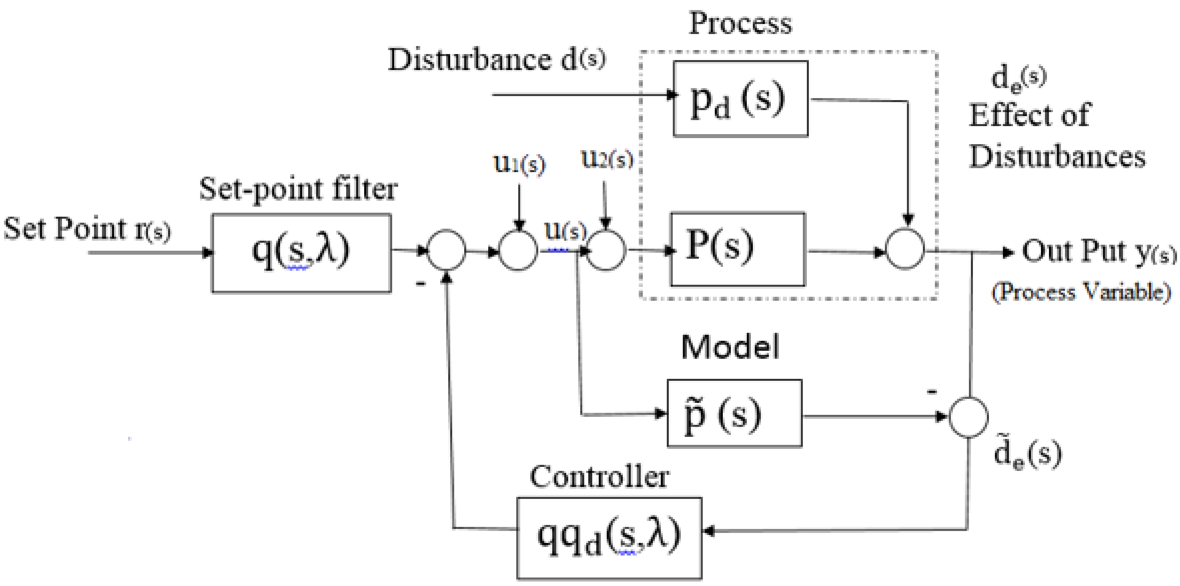

Figure 3.2 Block Diagram of 2DF IMC System with Additional Inputs (u_1 and u_2) for Deriving stability conditions.

For the explication of internal stability, this is adequate to take the control system output as the process outputs y(s).The output of the model is $\tilde{y}$(s), the control effort u(s), and the evaluation of the effect of disturbance on the process output $\tilde{d}_e$(s). The perfect model transfer function of the input and output is

$$\begin{bmatrix} y(s) \\ \tilde{y}(s) \\ u(s) \\ \tilde{d}_e(s) \end{bmatrix} = \begin{bmatrix} p(s)q(s) & (1-p(s)qq_d(s))p_d(s) & p(s) & (1-p(s)qq_d(s))p(s) \\ p(s)q(s) & p(s)p_d(s)qq_d(s) & p(s) & p^2(s)qq_d(s) \\ q(s) & p_d(s)qq_d(s) & 1 & p(s)qq_d(s) \\ 0 & p_d(s) & 0 & p(s) \end{bmatrix} \begin{bmatrix} r(s) \\ d(s) \\ u_1(s) \\ u_2(s) \end{bmatrix} \quad (3.8)$$

Suppose p(s), p_d(s) andq_d(s) are all stable, than all of the transfer function in Eq. (3.8) is stable. But, if p(s), p_d(s) or q(s) is not stable, then small variation in the inputs r(s), d(s), u_1(s) and u_2(s) will reason the outputs y(s), $\tilde{y}$(s), u(s) and $\tilde{d}_e$(s) to proceed with bound [7].

3.3.2 Single Loop Implementation of IMC for Unstable Process

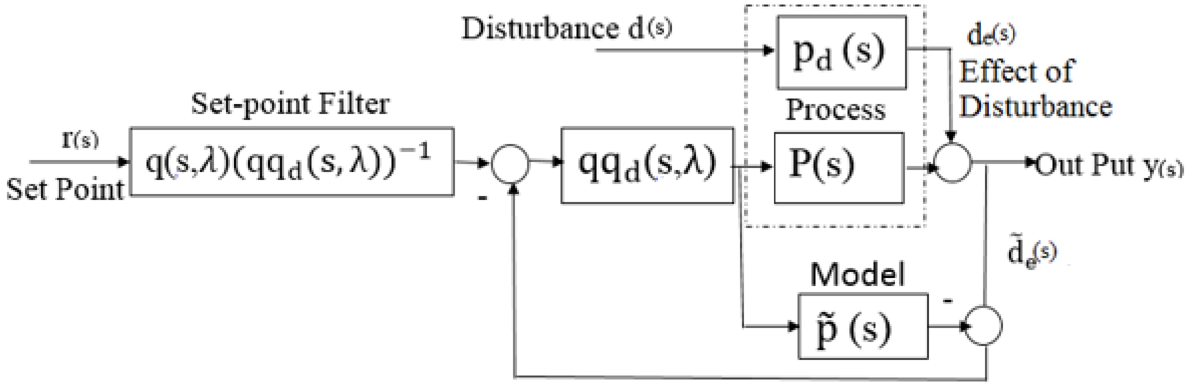

Figure 3.3 Single loop Configuration of a 2DF IMC system.

The single loop feedback control system has been obtained by collapse the two degrees of freedom control system figure 3.1.First, the 2DF IMC structure reconfigured in a single-loop feedback control system by moving the controller $qq_d(s, \lambda)$ out of the feedback path, then after the collapse the feedback loop around the model we get Fig. (3.4) which is shown in the below [12].

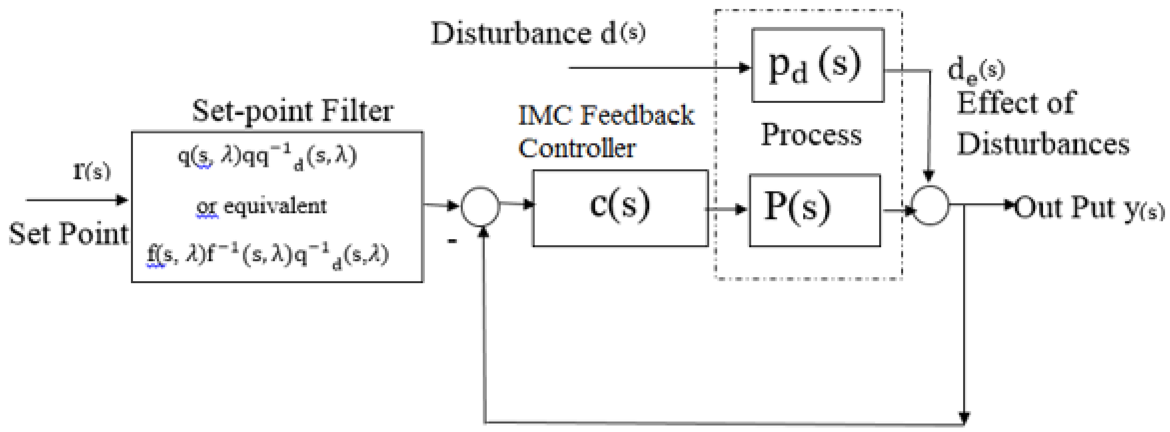

Figure 3.4 Feedback form of 2DF IMC system.

From the figure 3.4 the feedback controller c(s) is

$$c(s) = \frac{qq_d(s,\lambda)}{(1-\tilde{p}(s)qq_d(s,\lambda))} \tag{2.8}$$

The Fig. (3.3) set-point filter is converted into the set-point filter of Fig (3.4) using the relationship [9]

$$q(s,\lambda)\, q^{-1}(s,\lambda) = f\,(s,\lambda)\, f^{-1}(s,\lambda) \tag{3.9}$$

Where,

$$f(s,) = 1/(\lambda s + 1)^{r}$$

3.4 SIMULATION RESULTS AND DISCUSSIONS

Problem 3.4.1 1DF and 2DF Response to Process Disturbance

The process and model are

$$\tilde{p}_d(s) = p_d(s) = \tilde{p}(s) = p(s) = \frac{e^{-s}}{(4s+1)} \tag{3.10}$$

The 1DF IMC controller is

$$q(s) = \frac{(4s+1)}{(0.2s+1)} \tag{3.11}$$

Where, $\lambda = 0.2$ is a filter parameter for a noise amplification of 20.

The resulting control effort m(s) and output y(s), for a step disturbance are

$$m(s) = -\tilde{p}_{d(s)} q(s)/s \;= -\frac{e^{-s}}{s(0.2s+1)} \tag{3.12}$$

$$y(s) = \frac{(1-\tilde{p}(s)q(s)\tilde{p}_d(s))}{s} = \left(1 - \frac{e^{-s}}{(0.2s+1)}\right)\frac{e^{-s}}{(4s+1)s} \tag{3.13}$$

The time response of output y(s) and control effort m(s) is shown in the Fig. (3.5), where the long end of the output response can be recognized to the matter that the control effort tends to the steady state in about on time unit, when there is 1 unit time delay in the output, has not yet stopped increasing.

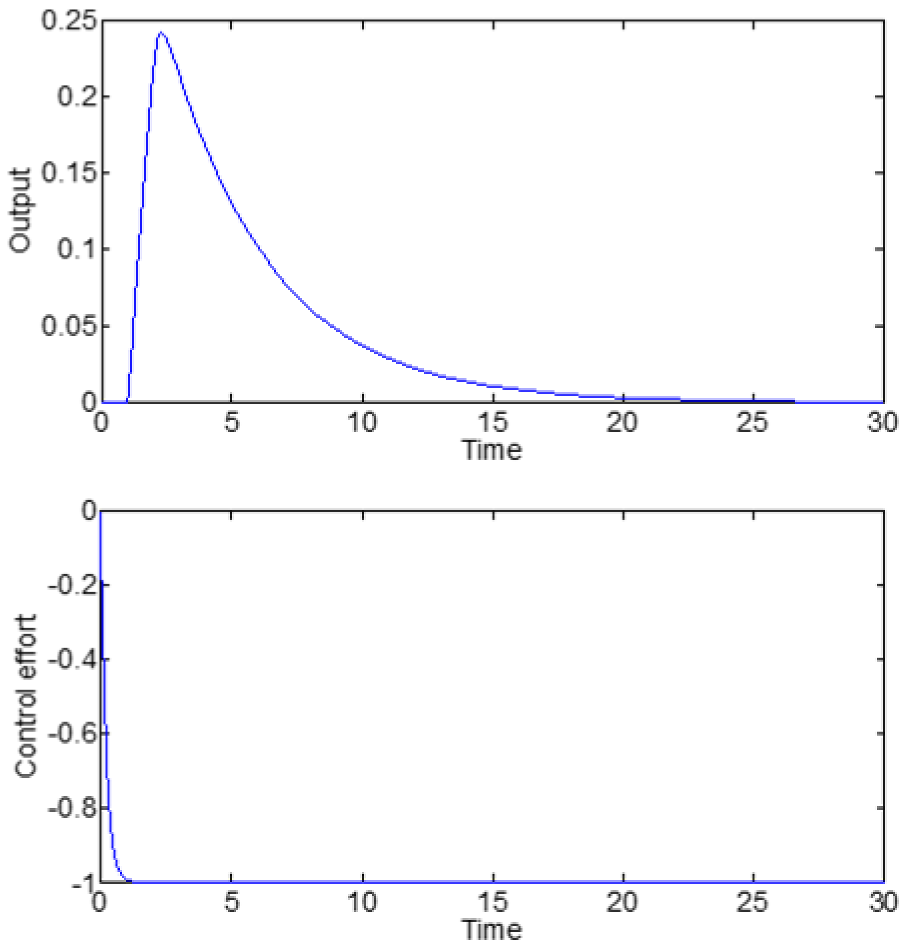

Figure 3.5 1DF IMC response to a step disturbance that gets over the process.

The 2DF IMC controller is

$$qq_d(s,\lambda) = \frac{(4s+1)(1.19s+1)}{(0.2s+1)^2} \tag{3.14}$$

Where,

Filter time constant $\lambda = 0.2$.

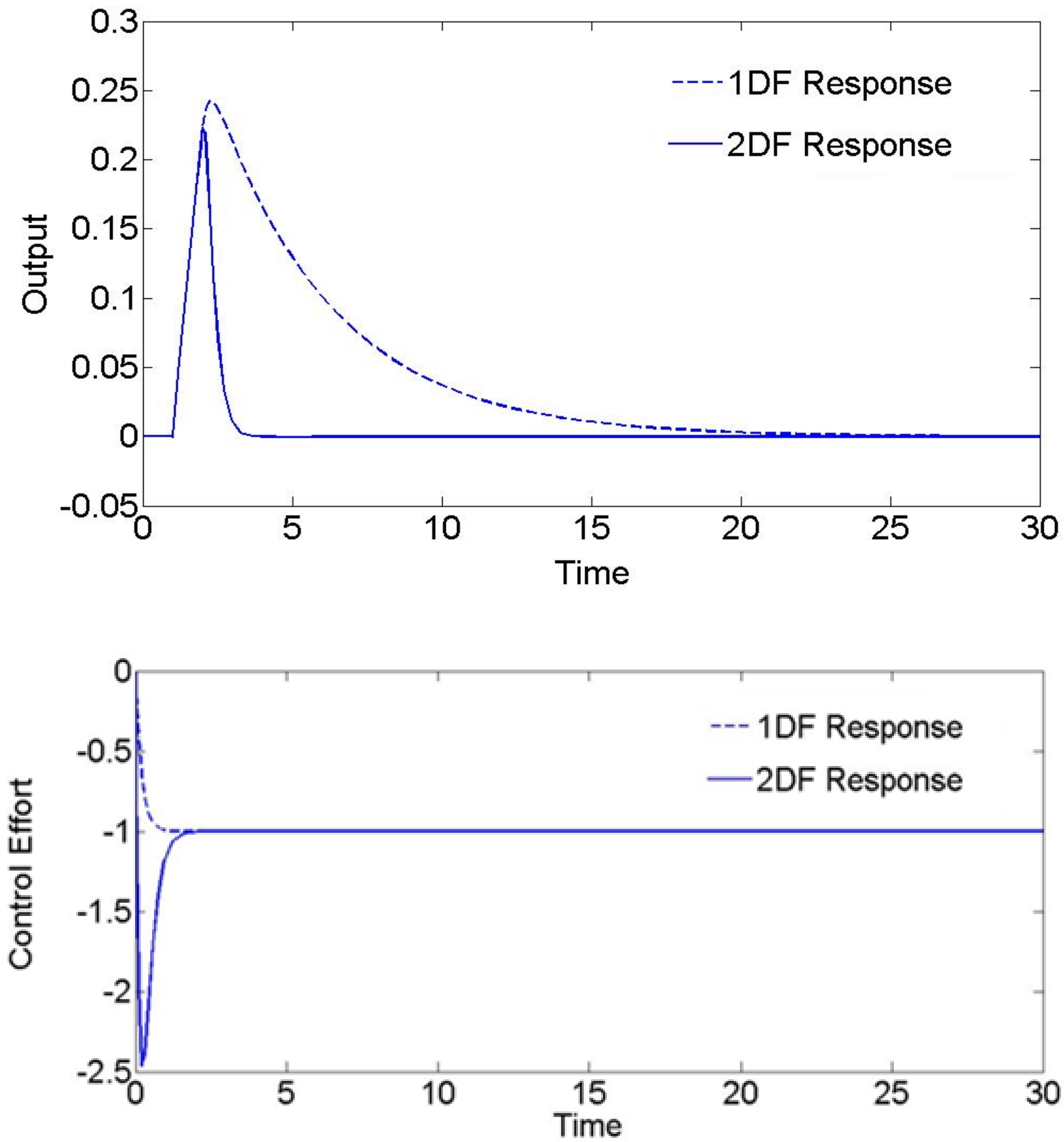

Figure 3.6 1DF IMC and 2DF IMC responses comparison to a step disturbance during process

Fig. (3.6) shows the comparison between 1DF and 2DF IMC response where 2DF IMC gives a better response as compared to 1DF IMC response. The 2DF IMC response takes a small settling time over a 1DF IMC response.

Problem3.4.2. For the feedback controller numerator coefficient β_i

The process and model are

$$\tilde{p}_d(s) = p_d(s) = \tilde{p}(s) = p(s) = \frac{e^{-s}}{(4s+1)} \tag{3.15}$$

In the first step we take the set-point filter q(s) so that the invertible portion of the process model $\tilde{p}(s)$ is inverted.

$$q(s) = \frac{(4s+1)}{(0.2s+1)} \tag{3.16}$$

In the second step, we design $q_d(s)$ so that the zeros of $(1-\tilde{p}(s)\, qq_d(s))$ cancel the poles of $p_d(s)$.Since $p_d(s)$ contains a single pole at -1/4.We select $q_d(s)$ as

$$q_d(s) = \frac{(\beta s+1)}{(\lambda s+1)} \tag{3.17}$$

The constant β is selected so that $(1-\tilde{p}(s)\, qq_d(s))$ contains a zero at s = -1/4. That is

$$(1-\tilde{p}(s)\, qq_d(s, \lambda, \beta))\Big|_{s=-1/4} = \left(1 - \frac{(\frac{-\beta}{4}+1)e^{1/4}}{(\lambda s+1)}\right) = 0 \tag{3.18}$$

Taking $\lambda = 0.02$ in Eq. (3.18) then we get β = 1.189

The output response is given by,

$$y(s) = \left[\frac{e^{-s}}{(4s+1)} - \frac{e^{-s}\,(1.189s+1)}{(4s+1)(0.2s+1)^2)}\right]\frac{1}{s} \tag{3.19}$$

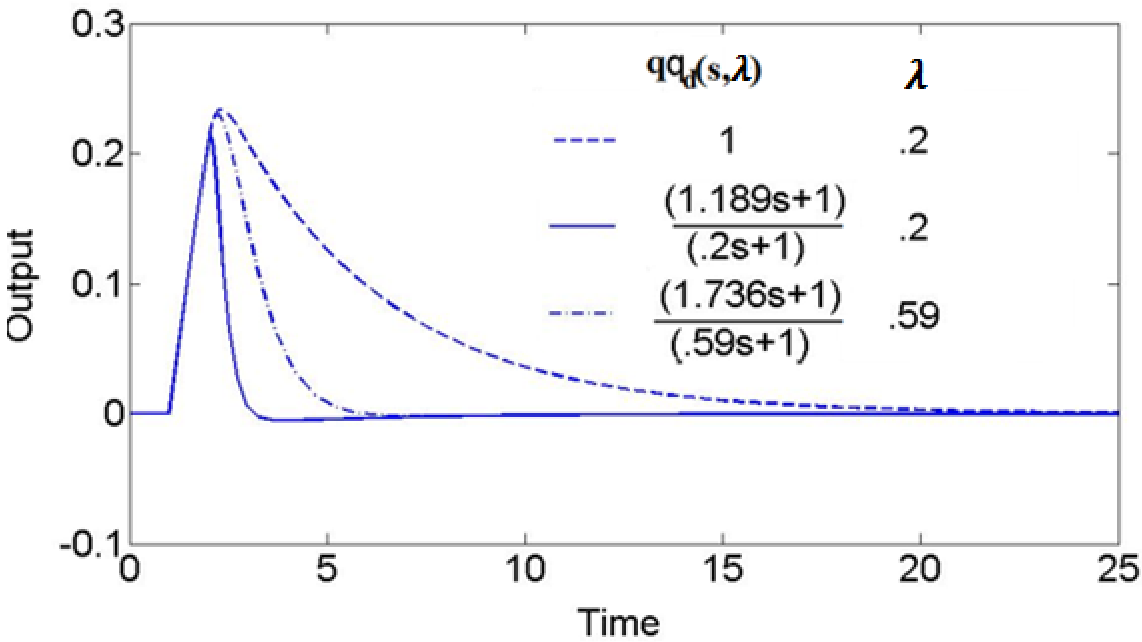

Figure 3.7 1DF IMC and 2DF IMC response comparison to a step disturbance to the process.

The filter time constant λ has been chosen as 0.2 for this is a no. that produces a noise amplification factor of 20 for the IMC controller q(s). But the noise amplification is represented by the higher no. of $|qq_d(j, \omega)/qq_d(0)|$ overall frequencies ω. Basically the higher noise amplification takes place at ω = ∞. For λ =0.2 and β = 1.198, we get the noise amplification factor as 119. Therefore λ has been taking a very small value. The time constant λ = 0.59 and β = 1.736 also satisfy the noise amplification factor and the Eq. (3.18). When the noise amplification factor is more than 20 has lost some of advantages of 2DF control system. However, a settling time 6 (sec.) still much better than a settling time 20 (sec).

Problem 3.4.3 Design for the Lead Process

The disturbance lag and process are

$$p_d(s) = p(s) = \frac{(s+1)^2 e^{-s}}{(s+1)^1} \tag{3.20}$$

The 1DF IMC controller is

$$q(s) = \frac{(s+1)^2}{(2s+1)(0.25s+1)} \tag{3.21}$$

The 2DF controller by canceling the disturbance lag (2s+1) linear term is

$$qq_d(s) = \frac{(s+1)^2(0.969s+1)}{(2s+1)(0.156s+1)^2} \tag{3.22}$$

The 2DF controller to cancel both disturbance ($(s+1)^2$) lags is

$$qq_d(s) = \frac{(s+1)^2(0.519s^2+1.35s+1)}{(2s+1)(0.235s+1)^3} \tag{3.23}$$

The output time responses for the all controllers are shown in the Fig. (3.8).Where 1DF controller gives a better performance as compared to 2DF controllers.

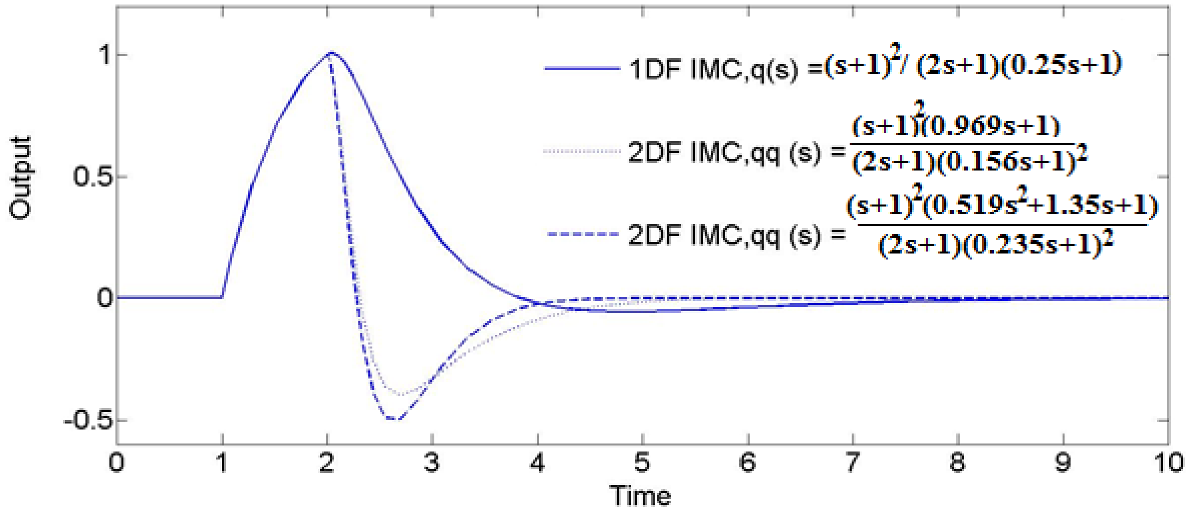

Figure 3.8 Comparison of 1DF and 2DF Responses to a Step Disturbance and to the Process.

Problem 3.4.4 Design for an Under Damped Process

The disturbance lag and process are

$$p_d(s) = p(s)= \frac{e^{-s}}{(s^2+0.2s+1)} \tag{3.23}$$

The 1DF controller is

$$q(s) = \frac{(s^2+0.2s+1)}{(0.22s+1)^2} \tag{3.24}$$

The 2DF controller is

$$qq_d(s) = \frac{(s^2+0.2s+1)(2.4s^2+0.32s+1)}{(0.6s+1)^4} \tag{3.25}$$

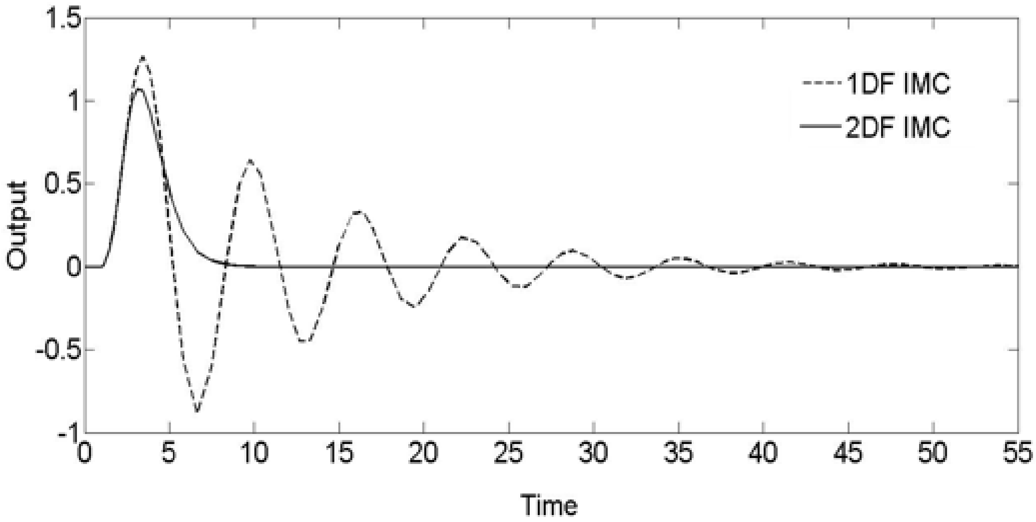

Figure 3.9 1DF and 2DF Responses to a Step Disturbance.

The 1DF and 2DF IMC response for a step disturbance has been shown in the below Fig. (3.9). The response of 2DF control system is far better than the 1DF control system. The 1DF IMC gives a more oscillatory response and settling time as compared to 2DF IMC response.

CHAPTER-4

IMC BASED CASCADE CONTROL SYSTEM

4.1 INTRODUCTION

4.1.1 Cascade Control System

A cascade control is one among the greatest well known methods for improving single loop performance. Cascade control will increase control system behavior above single-loop control whenever either: (i) Disturbance effect a secondary process output and measurable intermediate, which directly influences the primary process output which we want to control.(ii) the gain of the secondary process , included the actuators, in nonlinear[11].

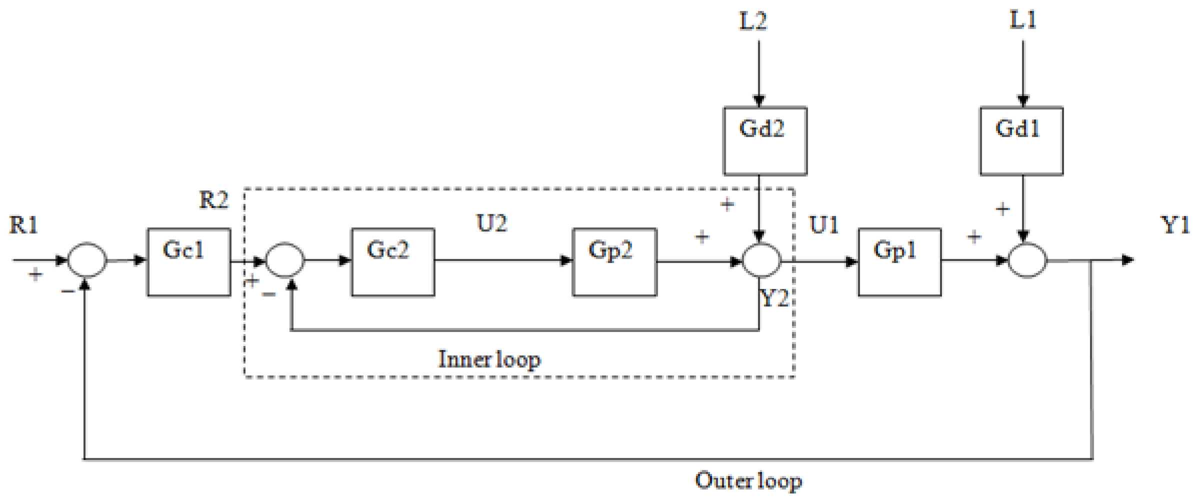

Figure 4.1 Block diagram of a cascade control system

The parameters of the cascade control system are

Gc1 - Primary Controller

Gc2 - Secondary Controller

Gp1 - Primary Process

Gp2 - Secondary Process

Gd1 and Gd2 – Disturbance gain

L2 - Secondary Disturbance

L1 – Primary Disturbance

Y1 – Primary Output

R1 – Primary Set-point

R2 – Secondary Output

4.1.2 Derivation for the Cascade Control System

The system output response is

$$Y2(S) = \frac{G_C2(S)2G_P2(S)}{1+G_C2(S)G_P2(S)}R2(S) + \frac{G_D2(S)}{1+G_C2(S)G_P2(S)}L2(S) \qquad (4.1)$$

The secondary closed-loop transfer function is

$$G_C2G_C1(S) = \frac{G_C2(S)G_P2(S)}{1+G_C2(S)2G_P(S)} \qquad (4.2)$$

The primary output is

$$Y1(S) = \frac{1+G_C2(S)G_P2(S)G_P1(S)}{1+G_C2(S)G_P2(S)}R2(S) + \frac{G_D2(S)G_P2(S)}{1+G_C2(S)G_P2(S)} + L1G_D1(S) \qquad (4.3)$$

After tuning the inner loop, we can use the following transfer function to design the outer controller

$$G_C1eff(s) = \frac{G_C2(S)G_P2(S)1G_P(S)}{1+G_C2(S)G_P2(S)} = G_C2G_C1(S)G_P1(S) \qquad (4.4)$$

And the closed-loop relationship for a primary set point change is

$$Y1(S) = \frac{G_C1(S)G_P1eff(S)}{1+G_C1(s)G_Peff1(S)}R1(S) = \frac{G_C1(S)G_C2G_C1(S)G_P1(S)}{1+G_C1(S)G_C2G_C1(S)G_P1(S)} \qquad (4.5)$$

4.2 CASCADE STRUCTURE AND CONTROLLER DESIGNS

The traditional block diagram of the cascade control system has been represented by Fig. (4.2). Where a cascade control system is consisting of a two PID controller and process. The objective of this traditional block has been to demonstrate methods for obtaining the parameters of the PID controller of figure 4.2 from a nicely-designed and nicely-tuned IMC cascade control system [8].

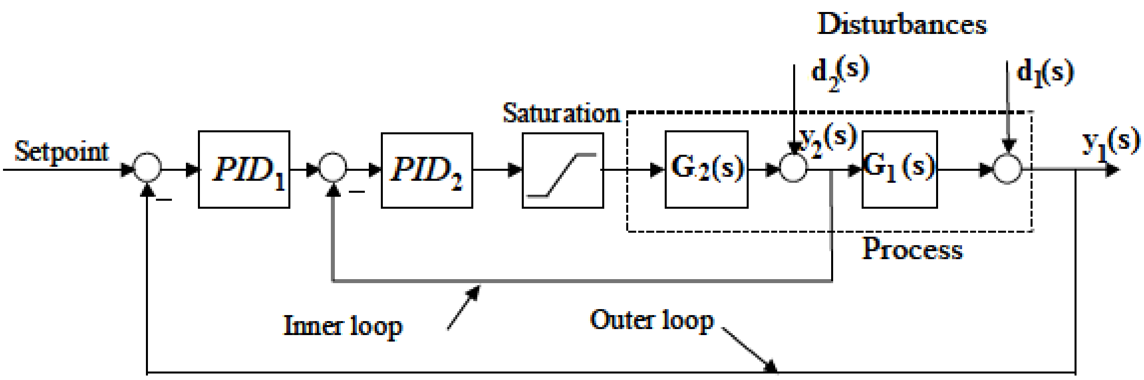

Figure 4.2 Traditional block diagram of cascade control system.

The IMC cascade block diagram has been shown in the figure 4.3 that fulfill the same purpose, such as Fig. (4.2). However, the IMC cascade structure of Fig. (4.3) is suitable because its advice that controller q_2(s) must be designed and tuned only to reduce the effect of the disturbance d_2(s) on the primary output y_1(s). The IMC control system is also suitable for the both controller’s outputs u_1(s) and u_2(s) that enter directly into the actuator. For the study of the design and tuning of IMC controllers the saturation block has been ignored [1].

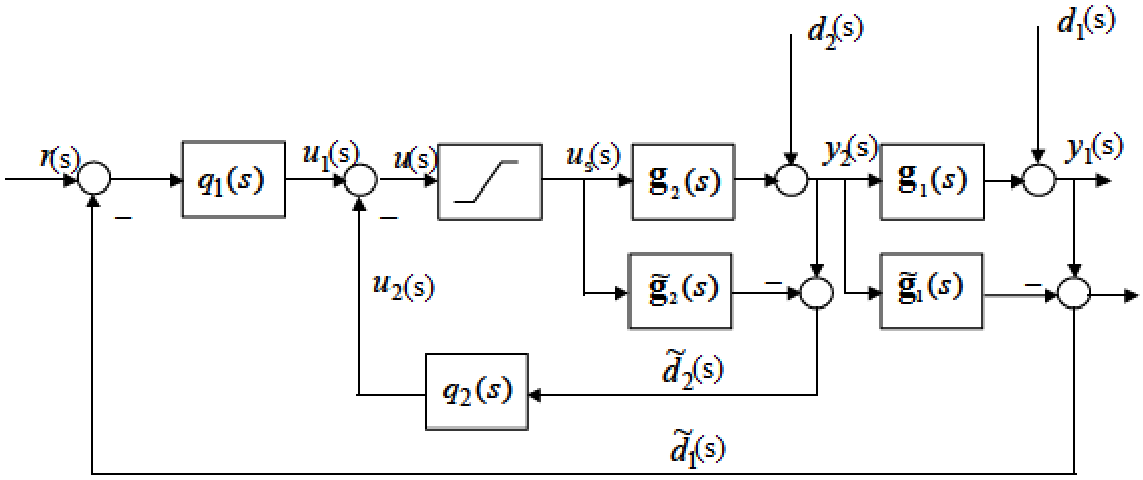

Figure 4.3 IMC cascade structure.

The secondary process output response is

$$y_2(s) = \frac{g_2(s)u_1(s)+(1-\tilde{g}_2(s)q_2(s))d_2(s)}{(1+(g_2(s)-\tilde{g}_2(s))q_2(s)} \tag{4.6}$$

Eq. (4.6) is the TF between the inner loop inputs $u_1(s)$ and $d_2(s)$ and the secondary process output $y_2(s)$.

The primary process output is

$$y_1(s) = \frac{g_1 g_2 q_1 r(s)+(1-\tilde{g}_2 q_2)g_1 d_2(s)+(1-\tilde{g}_1 g_2 q_1)+(g_2-\tilde{g}_2)q_2)d_1(s)}{(1+(g_1-\tilde{g}_1)g_2 q_1+(g_2-\tilde{g}_2)q_2)} \tag{4.7}$$

Eq. (4.7) is the TF between the set-point and disturbances.

Based on Eq. (4.7) we observe the following:

(i) In the case of lag time constant it the primary process$g_1(s)$ is larger than the secondary process$g_2(s)$ then the controller of the inner loop must be chosen so that zeros of (1-$\tilde{g}_2 q_2(s)$) cancel the small poles of $\tilde{g}_1(s)$.

(ii)The outer loop controller should has been inverted the entire process model $q_1(s)\tilde{g}_1\tilde{g}_2(s)$.

(iii) The IMCTUNE software has been used to tune the both controller $q_1(s)$ and $q_2(s)$.

The controller $q_2(s)$ has been tuned when the outer loop open and the controller $q_1(s)$ tuned when the inner loop closed. First of all we find the filter time constant λ_1 for $q_2(s)$ and then find λ_2 for $q_1(s)$. From equation (4.7) the denominator has been interacting the both controller $q_1(s)$ and $q_2(s)$ for the tuning. So, some adjustment of λ_2 must be necessary after obtainingλ_1[10].

After rearranging and ignoring the saturation block we get the modified form of a figure (4.3). The modified form is shown is the below Fig. (4.4).

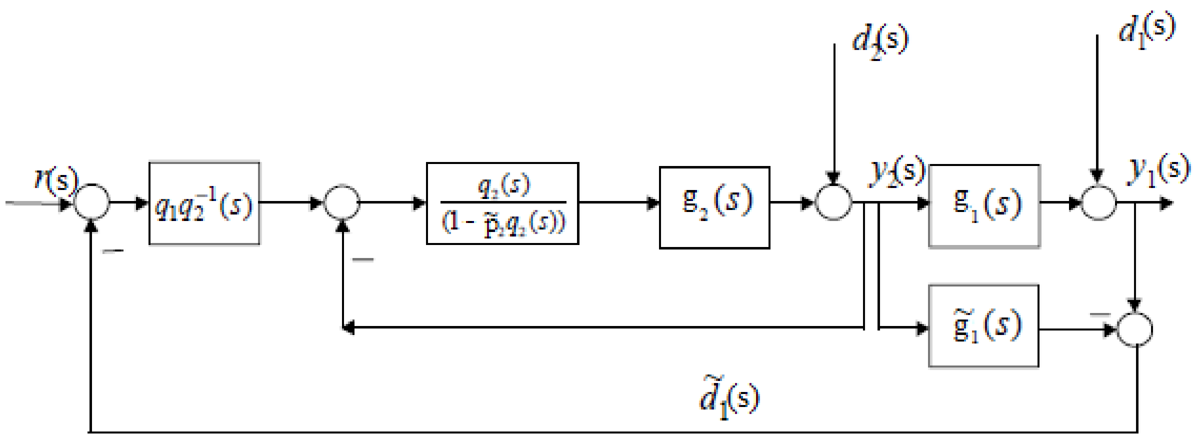

Figure 4.4 IMC cascade Control with a Simple Feedback Inner Loop.

In Fig. (4.4) we collapse the feedback loop through $\tilde{g}_1(s)$ so after exiting the inner loop alone we get a new Fig. (4.5).

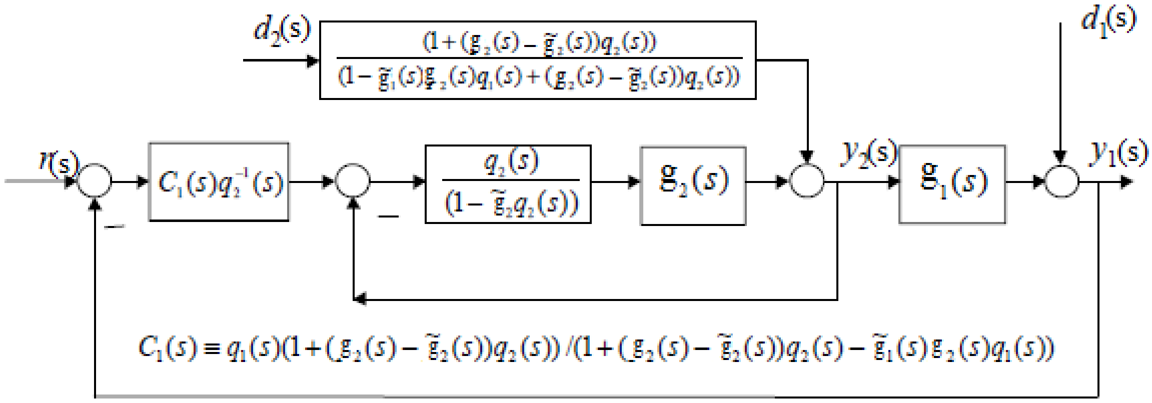

Figure 4.5 IMC cascade control with standard feedback form.

In Fig. (4.5) the controller$c_1(s)$ has not been considered because it contains the process transfer function$g_2(s)$, which is uncertain and cannot be made part of the controller, that's why we approximate the $g_2(s)$ with its model $\tilde{g}_2(s)$. In this case the controller become

$$c_1(s) \cong q_1(s) / (1-\tilde{g}_1(s)\tilde{g}_2(s)q_1(s)) \quad (4.8)$$

4.3 SIMULATION RESULTS AND DISCUSSIONS

4.3.1Design of the System when the Secondary Process has Faster Dynamics than the Primary Process

The primary and secondary process is

$$g_1(s) = \frac{k_1 e^{-\theta_1 s}}{\tau_1 s+1};\ 0.8 \le k_1 \le 1.2,\quad 17.5 \le \theta_1 \le 22.5,\quad 14 \le \tau_1 \le 16 \quad (4.9)$$

$$g_2(s) = \frac{k_2 e^{-\theta_2 s}}{\tau_1 s+1};\ 0.6 \le k_2 \le 1.8,\quad 2 \le \theta_2 \le 4,\quad 1 \le \tau_2 \le 3 \quad (4.10)$$

4.3.1.1 Designs of IMC System

The process model gain is

$$\tilde{g}_1(s) = \frac{1.2e^{-22.5s}}{14s+1} \tag{4.11}$$

$$\tilde{g}_2(s) = \frac{1.8e^{-4s}}{s+1} \tag{4.12}$$

Where, we use the lower bound time constant and upper bound gains and dead time for the process model.

The 2DF feedback controller for the inner loop is

$$q_2(s) = \frac{(s+1)(9.05s+1)}{1.8(4.4s+1)^2} \tag{4.13}$$

Where,

Filter time constant λ = 4.4.

Damping ratio ȿ = 9.05.

The 1DF IMC controller for the outer loop is

$$q_1(s) = \frac{(15s+1)}{2.16(16.87s+1)} \tag{4.14}$$

Where Filter time constant λ = 16.87.

The inner loop and outer loop controller are

Inner loop: $$\frac{q_2(s)}{(1-\tilde{g}_2 q_2(s))} \cong PID_2 = 1.79\left[\frac{127.169s^2+12.055s+1}{6.8933s^2+23.77s}\right] \tag{4.15}$$

Outer loop: $$c(s)q_2(s) \cong PID_2 = 0.4121\left[\frac{20.244s^2+12.055s+1}{177.135s^2+12.05s}\right] \tag{4.16}$$

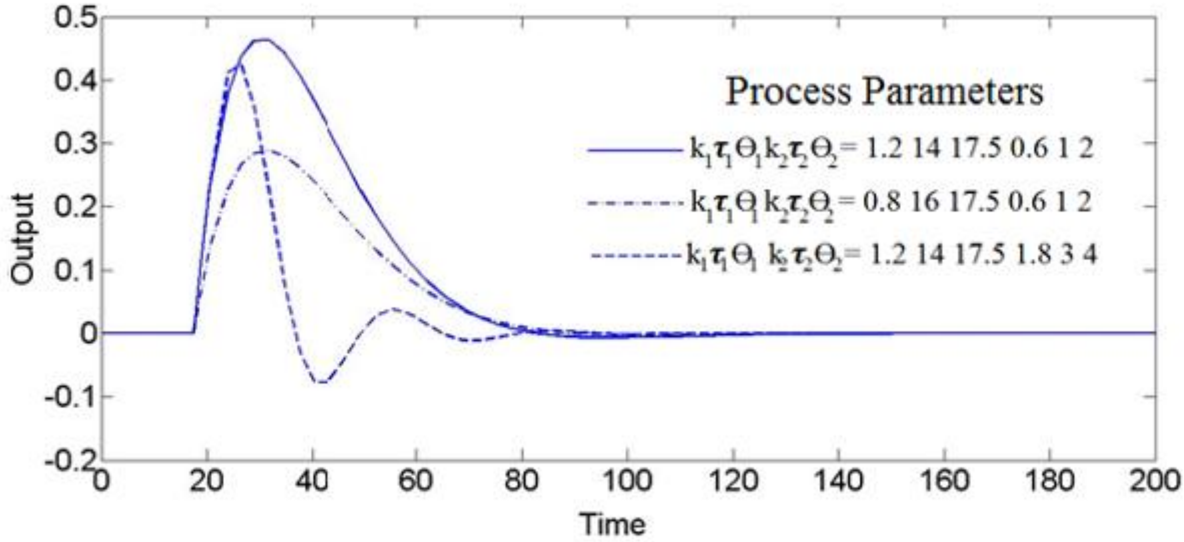

Figure 4.6 Response to a step inner loop disturbance $d_2(s)$ with the outer loop open.

The output response of a step inner loop disturbance of the different process has been shown in the Fig. (4.6).

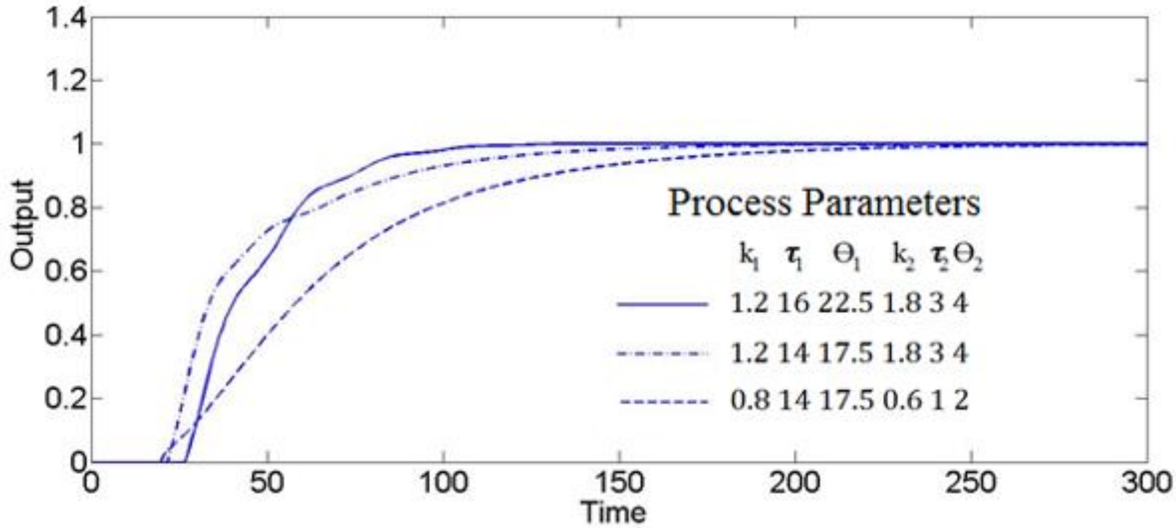

Figure 4.7 Step set-point response for the cascade control system.

IMC System Design for the Single loop

The single loop process model and controller are

$$\tilde{g}(s) = \frac{2.16e^{-26.5s}}{(15s+1)} \tag{4.17}$$

$$q(s) = \frac{(15s+1)}{2.16(14.3s+1)} \tag{4.18}$$

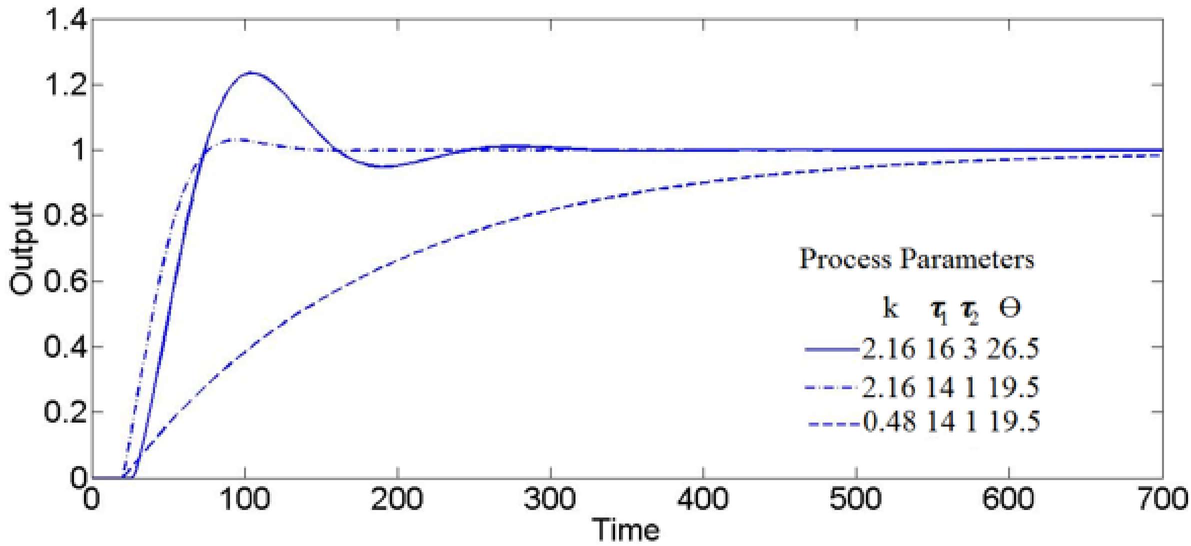

Figure 4.8 Step Set-point Responses for the Single-loop Control system.

From Fig. (4.7) and (4.8) we conclude that the fastest response of the single loop system is a little faster than the cascade system, however the slowest responses are significantly slower. Cascade system has been reduced the gain uncertainty in the inner loop process to improve the set-point response.

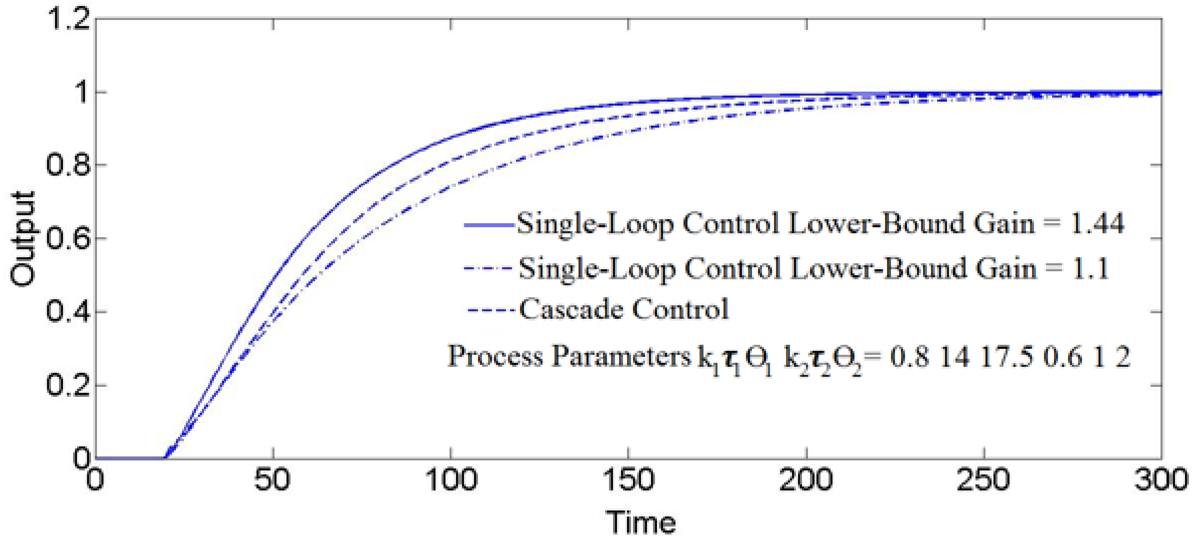

Figure 4.9 Comparison of Slowest Responses to a Step Set-point Change.

In Fig. (4.9) the cascade control system responses to the step set-point change when the outer loop is closed.

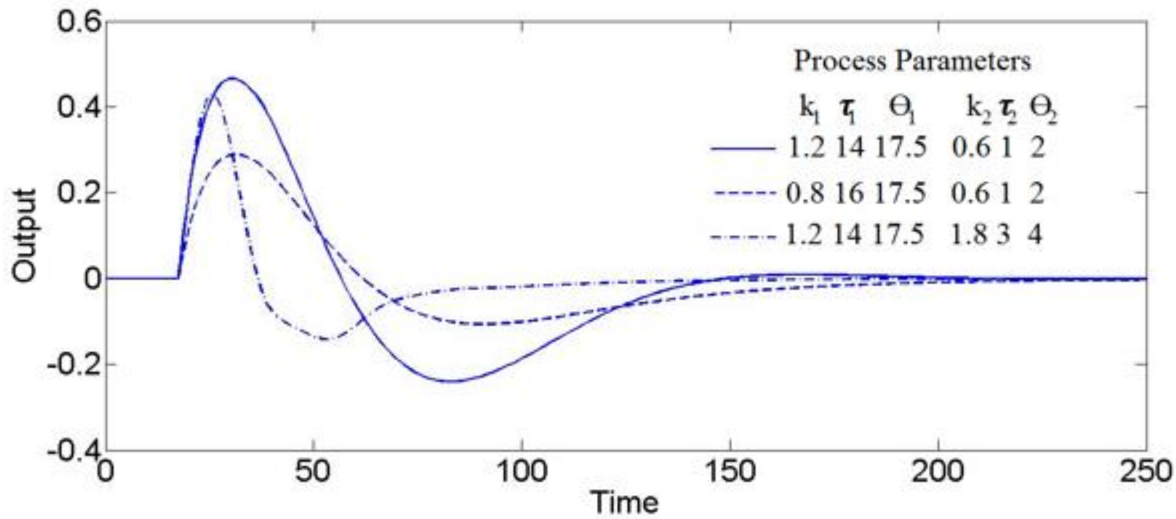

Figure 4.10 Responses to a Step Inner Loop Disturbance $d_2(s)$ with the Outer Loop Open.

For the Fig. (4.10) the 1DF IMC controller has been used on the response to a step disturbance in the inner loop.

The 1DF IMC controller is

$$q_2(s) = \frac{(s+1)}{1.8(4.18s+1)} \tag{4.19}$$

When the time constant of filter is 4.18 then we get Mp as 1.05.

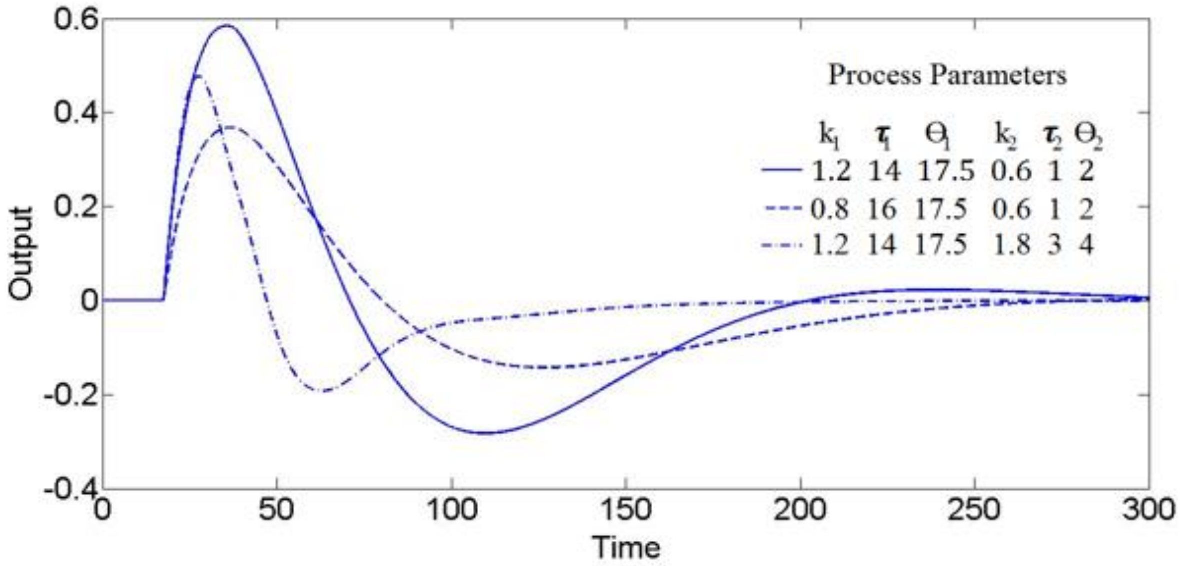

Figure 4.11 Responses to a Step Inner Loop Disturbance using the controller

$q(s) = \frac{(s+1)}{1.8(4.18s+1)}$.

The 1DF controller has slower inner loop disturbance response than 2DF controller.

4.3.1.2 Designs of PID Cascade Controller

The PID controllers are

Inner loop: $$\frac{q_2(s)}{(1-\tilde{g}_2 q_2(s))} \cong \text{PID}_2 = 1.79\left[\frac{127.169s^2+12.055s+1}{6.8933s^2+23.77s}\right] \tag{4.20}$$

Outer loop: $$c(s)q_2(s) \cong \text{PID}_2 = 0.4121\left[\frac{20.244s^2+12.055s+1}{177.135s^2+12.05s}\right] \tag{4.21}$$

Where controller$q_2(s)$ form a 2DF design, for this reason the response is called Cascade 2.

On using 1DF of IMC controller for $q_2(s)$, the equation for the inner loop PID controller is obtained as follows:

$$q_2(s) = \frac{(s+1)}{1.8(4.18s+1)}$$

Inner loop: $$PID_1 \cong 0.134\left[\frac{0.6633s^2+1.966s+1}{0.03168s^2+1.98s}\right] \quad (4.22)$$

Outer loop: $$PID_2 \cong 0.4956\left[\frac{209.58s^2+27.33s+1}{9.9752s^2+26.96s}\right] \quad (3.23)$$

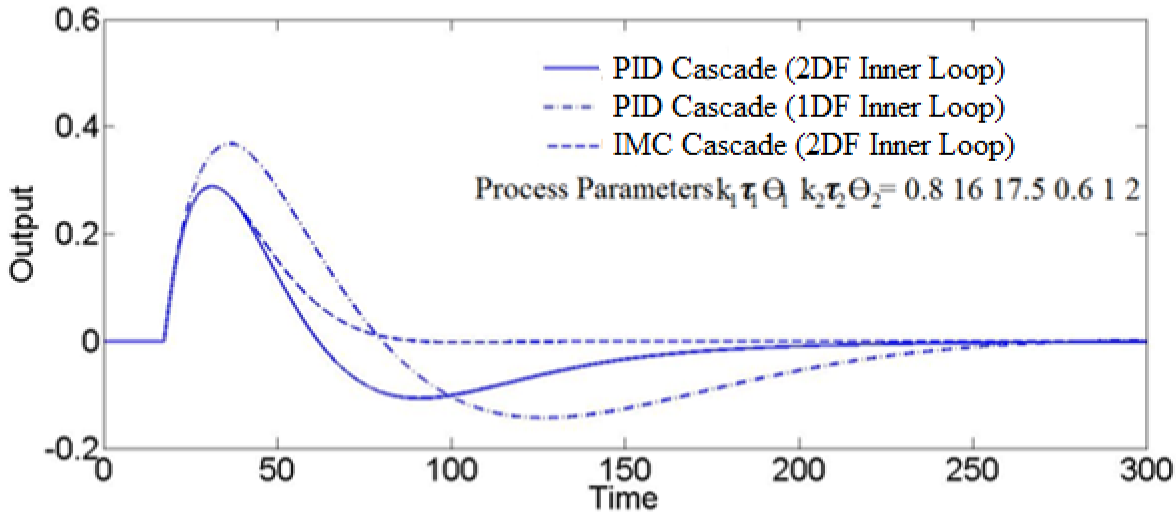

Figure 4.12 Comparison of Responses to a step Disturbance in the Inner Loop for $q_2(s) = (15s+1)/2.16(16.87s+1)$

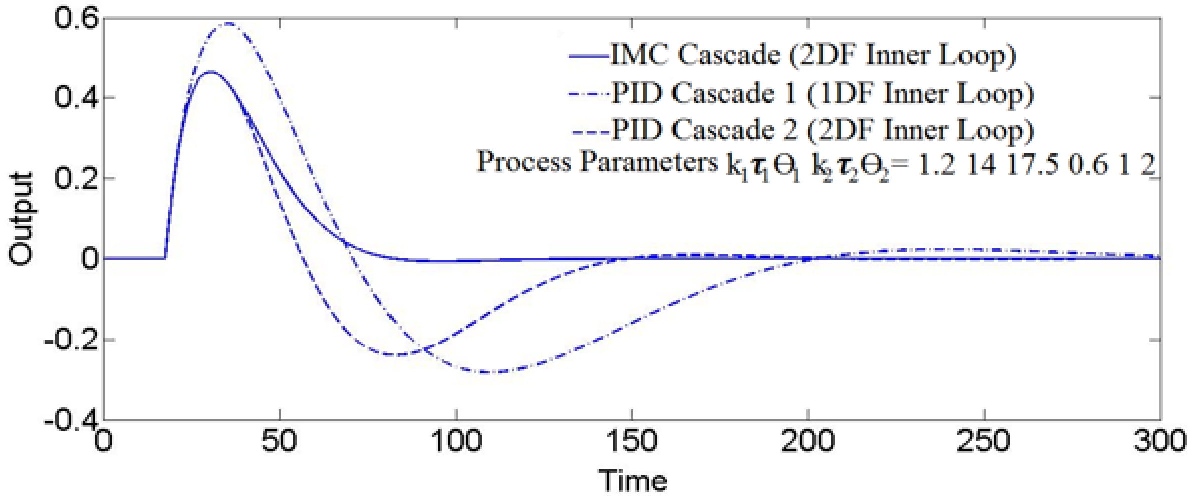

Figure 4.13 Comparison of Responses to a step Disturbance in the Inner Loop for $q_2(s) = (s+1)/1.8(14.8s+1)$.

Since $q_1(s)$ does not change the outer loop controller is same as Eq. (4.20). The responses in Fig. (4.12) and (4.13) using Eq. (4.23) are shown as cascade 1.The responses shows the advantages of an IMC outer loop as compared to PID outer loop.

4.3.2 Design of the System when the Primary Process and Secondary Process have same Dynamics

The primary and secondary process is

$$g_1(s) = \frac{k_1 e^{-\theta_1 s}}{\tau_1 s+1};\ 0.8 \le k_1 \le 1.2,\quad 3.5 \le \theta_1 \le 4.5,\quad 2.8 \le \tau_1 \le 3.2 \tag{4.24}$$

$$g_2(s) = \frac{k_2 e^{-\theta_2 s}}{\tau_1 s+1};\ 0.6 \le k_2 \le 1.8,\quad 2 \le \theta_2 \le 4,\quad 1 \le \tau_2 \le 3 \tag{4.25}$$

4.3.2.1 Design of IMC System

The process model gain is

Where, we use the lower bound time constant and upper bound gains and dead time for the process model

$$\tilde{g}_1(s) = \frac{1.2e^{-4.5s}}{2.8s+1},\quad g_2(s) = \frac{1.8e^{-4s}}{s+1} \tag{3.26}$$

The IMC controllers are

$$q_2(s) = (s+1)/1.8(2.8s+1) \quad (4.27)$$

$$q_1(s) = (3.8s+1)/2.16(5.24s+1) \quad (4.28)$$

Inner loop: $$\mathrm{PID}_1 = \cong 0.485\left[\frac{20.576s^2+8.122s+1}{0.976s^2+8s}\right] \quad (4.29)$$

Outer loop: $$\mathrm{PID}_1 = \cong 0.178\left[\frac{1.044874s^2+2.2028s+1}{0.049704s^2+2.18s}\right] \quad (4.30)$$

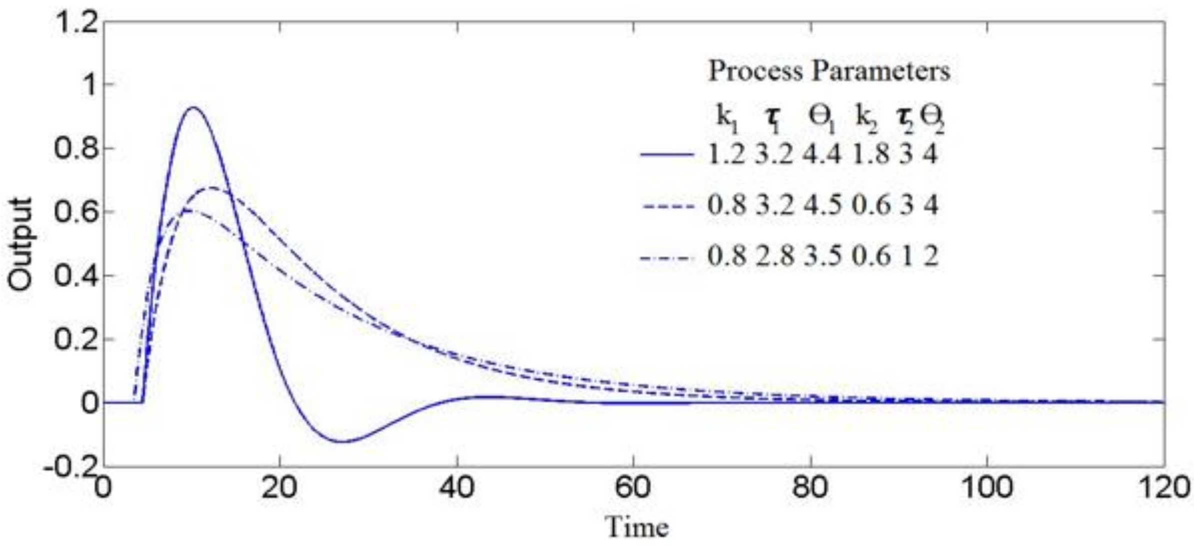

Figure 4.14 Unit Step Disturbance $d_2(s)$ Responses for the IMC Cascade Control system.

Primarily design of 2DF controller for inner loop gives the time of time constant of 2.8 before an Mp of 1.05 is achieved for partial sensitivity function. For this case the feedback controller the inner loop is taken to be 1DF controlled and the time constant of the filter is tuned using partial sensitivity functions like the design of 2DF.The disturbance responses of IMC cascade control system has been shown in the Fig. (4.14). The Eq. (4.26), Eq. (4.27) and (4.28) shows the respective models and controllers.

The Responses in Fig. (3.14) is compared with the single loop control system. By combining the Eq. (3.24) and (3.25) we get a new related model and controller:

$$g(s) = \frac{k_1 k_2 e^{-\theta s}}{(\tau_1 s+1)(\tau_2 s+1)} \tag{4.31}$$

Where

$0.8 \leq k_1 \leq 1.2,\quad 0.6 \leq k_2 \leq 1.8,\quad 2.8 \leq \tau_1 \leq 3.2,\quad 1 \leq \tau_2 \leq 3,\quad 5.5 \leq \Theta \leq 8.5,$

$$g_d(s) = \frac{k}{(\tau_1 s+1)} \tag{4.32}$$

The single loop model and controller is

$$\tilde{g}(s) = \frac{2.16e^{-8.5s}}{(3.8s+1)} \tag{4.33}$$

$$q(s) = \frac{(3.8s+1)}{2.16(6.31s+1)} \tag{4.34}$$

The disturbance dead time is neglected by Eq. (4.32) because the effective arrival time of the disturbance is only changed and so it can't be distinguished from the disturbance. The process lags of the first order system model given by Eq. (4.33) is approximately the sum of the time constant of to first order process lags. Although the disturbance $d_2(s)$ enters into the primary output through the lag given by Eq. (4.32), we get the 1DF controller given by Eq. (4.34) as a single loop controller is used.

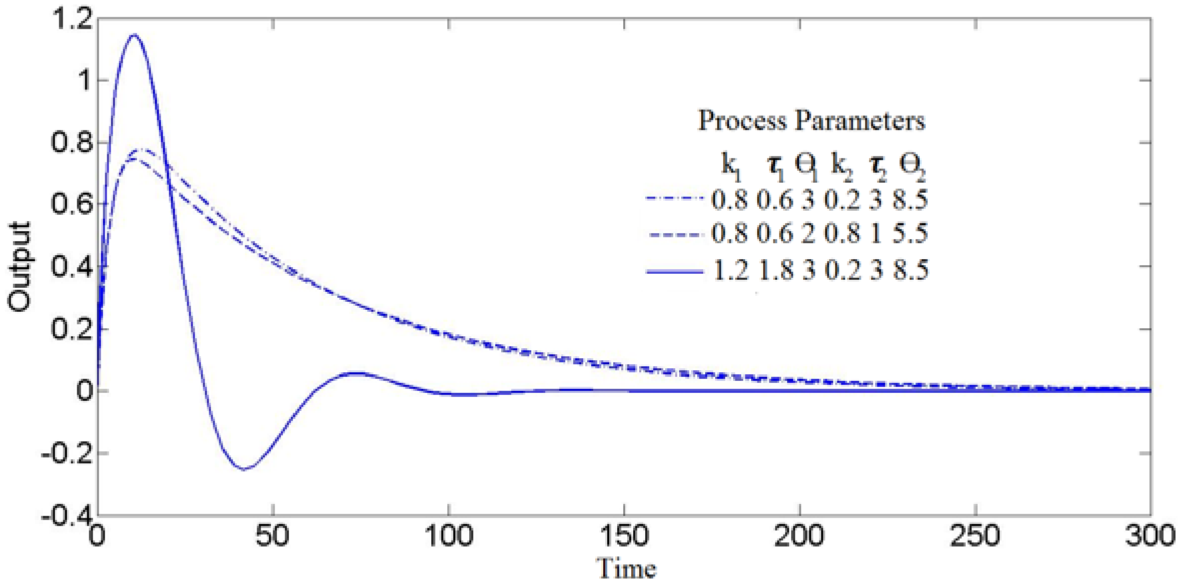

Figure 4.15 Single-loop Control System Responses to a Step Disturbance in $d_2(s)$.

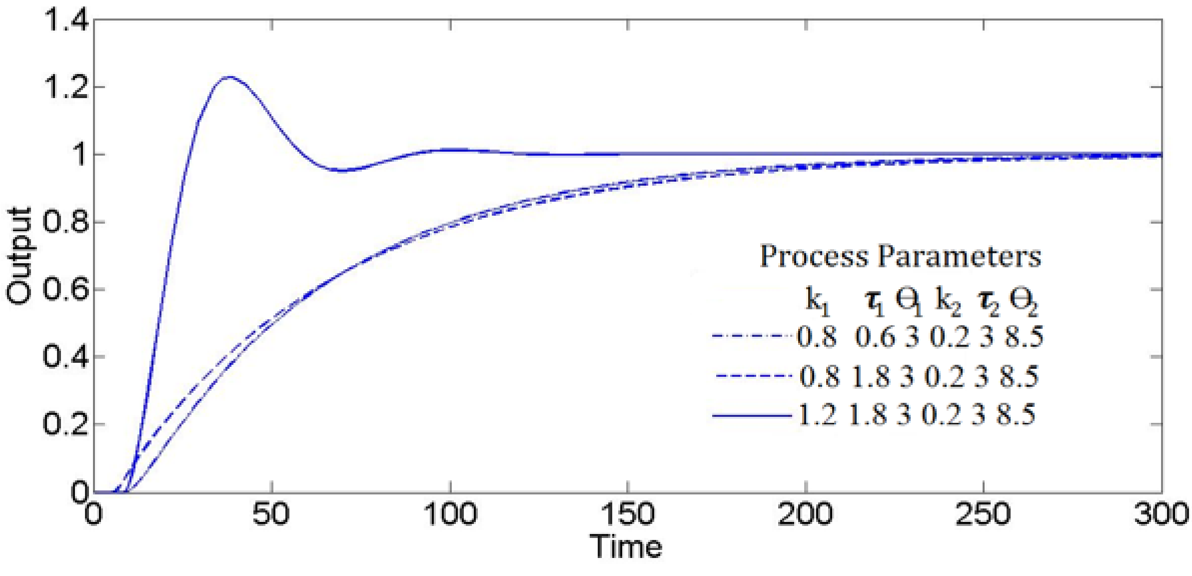

Figure 4.16 Step Set-point Responses for the Single Loop Control System.

The responses of single loop given in Fig 4.15 are slower than cascade control loop which is approximately twice its value and is shown in figure 4.14. The time scale in Fig. (4.15) is 0 to 300 but time scaling Fig. (4.14) is 120 and also the disturbance peak height is more in Fig. (4.15) than in Fig. (4.14).

Even though the IMC inner loop is replaced with a feedback controller as shown in Fig. (4.2) and the feedback controller is approximated the PID controller given by Eq. (4.33) and disturbance responses of a Fig. (4.14) remain unchanged. There for there is no change in the performance of the mixed IMC-PID cascade control system.

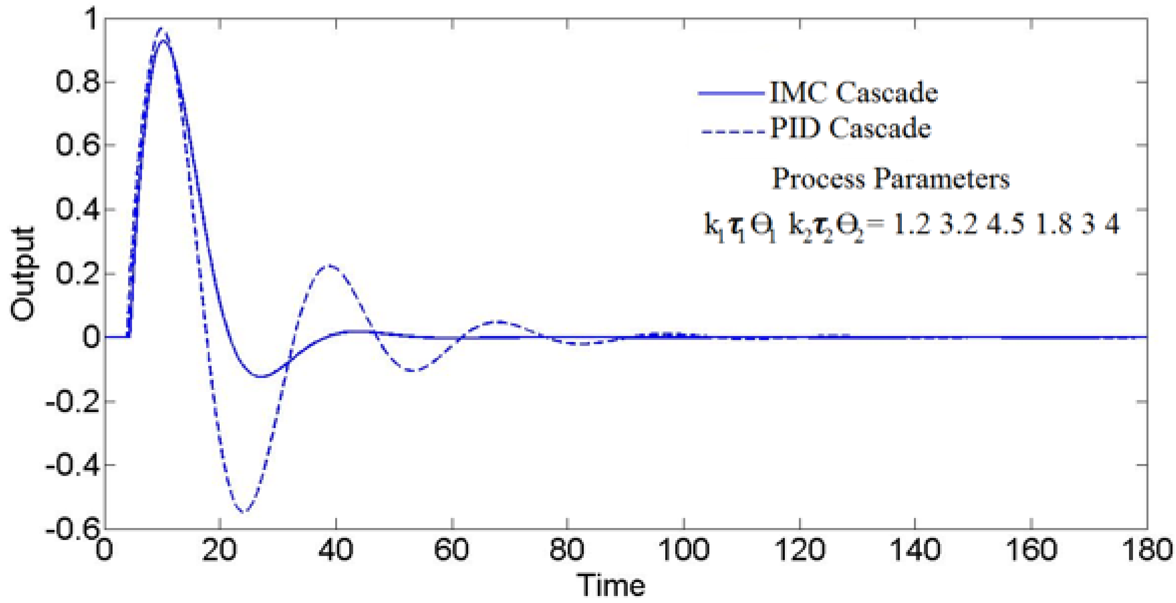

Figure 4.17 Comparison of Responses to a Step Disturbance in Inner Loop.

The response of the inner loop disturbance $d_2(s)$ for the traditional cascade configuration has been in the Fig. (4.17) by using the PID controllers whose equation are given in Eq. (4.33) and Eq. (4.34). By using the upper bound parameters the response for a process is more oscillatory and we get an overshoot of 21 percent. For the set point response to the same process because of the interaction between the inner and outer loops.

CHAPTER-5

CONCLUSION

5.1 CONCLUSION

5.2 FUTURE SCOPE

5.1 CONCLUSION

In this project I tried to implement and design the 1DF and 2DF IMC controller and modified the internal model control for the cascade system. For this I have taken 1DF IMC controller for the IMC cascade system outer loop and 2DF IMC controller for the inner loop. By using MATLAB simulation software I have implemented the single loop and IMC cascade control responses. By using the 2DF controller for the cascade control inner loop, we achieve the best set-point tracking as well as disturbance rejection in that region Cascade control has improved control system performance over single loop control. The 2DF controller gives good response over 1DF controller. 2DF controller takes less settling time as compare to 1DF controller to reach the stable state.

5.2 FUTURE SCOPE

We have worked on IMC based cascade control system, but it for better robustness and increases sing plant efficiency we use. By increasing the number of the controller we can expand the multi cascade system.

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